ABSTRACT

The International Fusion Materials Irradiation Facility (IFMIF) is a high energy neutron irradiation facility which generates a 14MeV neutron flux with D–Li (Deuterium-Lithium) stripping reactions. It's an international research project designed to test materials specimens since this environmental conditions recreate nuclear fusion power plants atmosphere. Therefore, the achieved materials database will be utilized to build the inner walls, the blanket components, the coating and the isolation of these future power plants.

An overall availability of 70% is required by IFMIF to guarantee the proper materials irradiation; therefore the Reliability, Availability, Maintenance and Inspectionability (RAMI) analyses are necessary in the run up to IFMIF construction. These analyses are carried out by the Nuclear Engineering Research Group (NERG) in cooperation with CIEMAT. Specifically, the following project focuses in the Remote Handling (RH) system used in the test and the target maintenance tasks. The staff cannot have access to this area owing to the effective dose exceeds the minimum hand maintenance zone (650μSv/year) due to the activation of structural materials. Human influence will be an essential factor in these maintenance chores; for this reason, this project is a first milestone towards the merge between RAMI and Human Reliability Assessment (HRA).

The Human Cognitive Reliability (HCR) model is the means of quantifying the cognitive part influence in the Human Failure Event (HFEs) while Technique for Human Error Rate Prediction (THERP) is used for the assessment of the action part. The combination of those methods is called Systematic Human Action Reliability Procedure (SHARP) and it will provide us the tool in order to introduce the human factor in the RAMI analyses as a basic event.

The report shows the strong human factor influence in the RH tasks and, consequently, the need to develop a tool which quantifies these effects. Moreover, some conceptual improvements of the final equipment design are introduced in those operations or HFEs that induce a high level of unavailability. Some of these recommendations are the implementation of instrumentation in the RH attachment tool or clamp, the implementation of an infrared camera in the cranes or a virtual confinement volume generated by control software integrated in the RH where the operator actuates.

Finally, once all the improvements are taken into account, the mean availability exceeds the objective value in the availability allocation of 99.1% during the RH operations: for curative interventions is 99.3% and for the long maintenance period is 95.8%.

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1. Glossary

AC	Access Cell
ACMC	Access Cell Mast Crane
ATHEANA	A Technique for Human Error Analysis
CDA	Concept Design Activity
CDR	Comprehensive Design Report
CFTM	Creep Fatigue Test Module
CIEMAT	Centro de Investigaciones Energéticas, Mediambientales y Tecnológicas
CMS	Combined Manipulator System
D	Deuterium
DDD	System Design Description Document
DEMO	Demonstration Power Plant
ECRIS	Electron Cyclotron Resonance Ion Source
EF	Error Factor
ET	Event Tree
FEEL	Fusion Energy Engineering Laboratory
FMECA	Failure Modes, Effects, and Criticality Analysis
FP_C	Cognitive Failure Probability
FP_M	Manual Failure Probability
FT	Fault Tree
HCR	Human Cognitive Reliability
HEBT	High Energy Beam Transport
HEP	Human Error Probability
HFE	Human Failure Event
HFTM	High Flux Test Module
HRA	Human Reliability Assessment
HROC	Heavy Rope Overhead Crane
IFMIF	International Fusion Materials Irradiation Facility
INPO	Institute of Nuclear Power Operations
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
KEP	Key Element technology Phase report
KeV	Kiloelectron-volt

LBVM	Liquid Breeder Validation Module
LEBT	Low Energy Beam Transport
LFTM	Low Flux Test Module
Li	Lithium
MEBT	Middle Energy Beam Transport
MeV	Megaelectron-volt
MFTM	Medium Flux Test module
MG	Master Grapple
MTTR	Mean Time To Repair
NERG	Nuclear Engineering Research Group
NSS	Neutron Spectrum Shifter
NUREG	NRC Regulatory Guide
PCP	Piping and Cabling Plug
PIE	Post Irradiation Examination
PSF	Performance Shaping Factor
r	Failure rate (Parametric analysis tables)
RAMI	Reliability, Availability, Maintenance and Inspectionability
RFQ	Radio Frequency Quadrupole
RH	Remote Handling
SHARP	Systematic Human Action Reliability Procedure
SRF	Superconducting Radio Frequency
STAR	Stop, Think, Act and Review
T	Tritium
TA	Target Assembly
TC	Test Cell
TCCP	Test Cell Cover Plate
THERP	Technique for Human Error Rate Prediction
TM	Test Module
TMHC	Test Module Handling Cell
TMIH	Test Module Interface Head
Tr	Time to repair (Parametric analysis tables)
TRTM	Tritium Release Test Module
TSP	Top Shielding Plug
UA	Unsafe Action

2. Preface

This Project has been developed from September 2012 to April 2013. The Fusion Energy Engineering Laboratory (FEEL) belonging to the Nuclear Engineering Research Group (NERG) in cooperation with Centro de Investigaciones Energéticas, Mediambientales y Tecnológicas (CIEMAT) has been working in the International Fusion Materials Irradiation Facility (IFMIF) international project since January 2007. The tasks carried out by the FEEL during these years have dealt with IFMIF availability goals. Their studies have shown the Reliability, Availability, Maintenance and Inspectionability (RAMI) analysis for each facility into IFMIF; the test, the accelerator and, in conjunction with this master thesis, the RH Remote Handling (RH) system. Moreover, the FEEL has succeeded creating a strong failure rate and mean time to repair (MTTR) database for a large number of components used into every facility.

The perception of human factor could have a significant influence on the maintenance tasks performed by the RH system appears on the run up to RH Failure Modes, Effects, and Criticality Analysis (FMECA) design. So, it was necessary to devise a new tool to estimate how the human action affects these maintenance tasks and the global downtime of the facility.

Getting involved in a worldwide project related with nuclear fusion power and achieving a working method in order to merge the Human Reliability Assessment (HRA) with the RAMI analysis were a positive source of motivation and a great chance to work in a master thesis project.

3. Introduction

This project explains a first HRA associated with the IFMIF RH system used in the maintenance tasks.

A HRA is a tool with which the RAMI team attempts to predict how the human factor that exists in some tasks involved in a certain system can affect its global downtime. In order to accomplish this goal; events, which are caused by human tasks, are given the status of "system components" as basic events and they can be used in a RAMI analysis.

For doing a merge between RAMI analysis and HRA the following inputs are needed:

- A model of the considered system. The RH system in this case.
- A planned human tasks procedure. The test and target facilities maintenance tasks carried out by the RH system.
- A FMECA (Failure Modes, Effects, and Criticality Analysis) of the considered system.
- A Human Failure Event (HFE) database with their Human Error Probability (HEP).
- A reliability database of every system component.

Although these inputs were difficult to obtain and many of them required a large amount of assumptions, all the provided information has been properly referenced. The model was designed taking into account the initial *Concept Design Activity* (CDA) [1] of IFMIF and the different modifications that have been introduced *at Key Element technology Phase report* (KEP) [2], *Comprehensive Design Report* (CDR) [3] and more updated alternatives. Specifically, the arrangement of the RH system, the Test Cell (TC), Access Cell (AC) and the rest of the cells adopt the *System Design Description Document II* (DDD-II) [4] pattern. In HEP estimation part, the primary source consulted was *the Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications* [5]. More references will be mentioned in the text.

This study is a first model and an approach that should be improved and updated at the time when the human tasks procedure and the design will be the final ones.

3.1. Objectives

The main aim of the project has been the development of a tool to quantify the HEP (Human Error Probability) associated with any human task and the insertion of it in the RAMI reviews of IFMIF. Nevertheless, some prior and other objectives have to be reached: the modification of the RH FMECA including the human factor, the design of the HFEs belonging to the RH FMECA database, the creation of all the Unsafe Actions (UA) and the Event Trees (ET) belonging to every HFE, the estimation of all the HEP taking into account the cognitive and manual part as the method states and, finally, the merge between the HRA and the RH RAMI analysis.

3.2. Scope

The scope of the text includes from a brief explanation of fusion power, International Thermonuclear Experimental Reactor (ITER) and Demonstration Power Plant (DEMO), IFMIF and the facilities it is developed with; until the merge between the RAMI and the HRA. In addition, the RH system design is widely described.

Nonetheless, as it already mentioned the main aim of the project has been the development of a tool to quantify the HEP associated with any human task and the insertion of it in the RAMI reviews of IFMIF. This instrument for HEP calculation had to fulfill methods already validated; for this reason, different HRA sources have been studied and properly referenced throughout the report.

4. Fusion power

4.1. The nuclear fusion

Nuclear fusion is the reaction by which two or more atomic nuclei collide and join together to form a new heavier atomic nucleus. The fusion of two nuclei with lower masses than iron or nickel (which have the largest binding energy per nucleon) generally releases energy, while the fusion of nuclei heavier than iron absorbs energy. The matter is not conserved during the process due to the mass defect. So, fusion generally occurs for lighter elements only and their mass loss is converted to energy released following the Einstein equation $E=m \cdot c^2$.

In spite of this energy is generated by the stars by means of nuclear fusion of hydrogen nuclei into helium; their production artificially with the aim of generating electricity is a laborious task. This research and development work has been conducted for over the last 60 years and it has encountered with great scientific and technological challenges. The electrostatic repulsion force between the positively charged protons of the nuclei has to be overcome before fusion can occur. If two nuclei can be brought close enough together (very short distance between them), the nuclear force of attraction is stronger than the electrostatic and the last one can be surpassed. Therefore the prerequisite for fusion is that the nuclei have enough kinetic energy that they can approach each other despite the electrostatic repulsion. This minimum energy is called the Coulomb barrier.

The Lawson criterion defines the conditions needed for a fusion reaction to reach the ignition, that is, that the heating of the plasma by the products of the fusion reactions is sufficient to maintain the temperature of the plasma against all losses without external power input. These conditions are three:

- The electron density, n_e
- Plasma temperature, T
- The confinement time, τ_e

And the relationship if we want to obtain the ignition is:

$$n_e \cdot T \cdot \tau_e \geq 10^{21} \frac{KeV \cdot s}{m^3} \qquad \text{(Eq. 4.1)}$$

The reaction cross section σ is a measure of the probability of a reaction and the Coulomb barrier is smallest for isotopes of hydrogen, as their nuclei contain only a single positive charge.

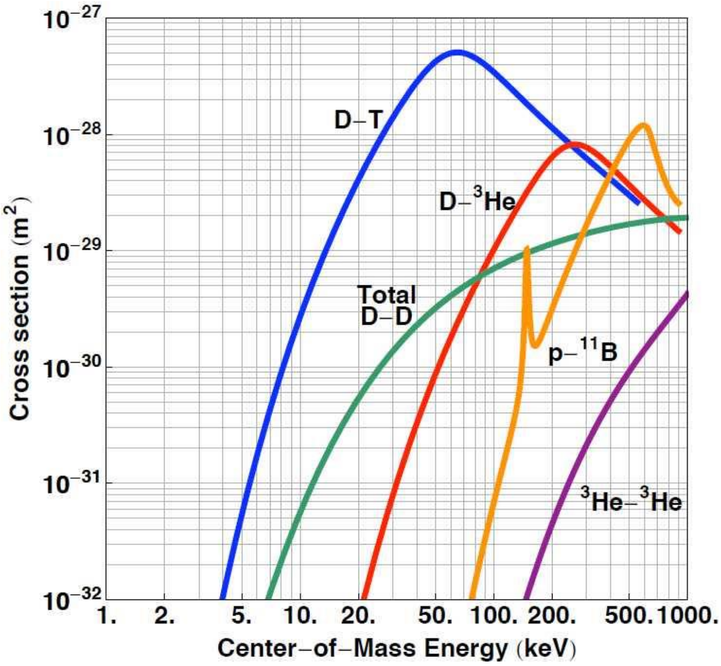

Fig. 1 – Cross section for different fusion reactions

The previous graphic shows that the reaction D-T (Deuterium-Tritium) is the easiest to achieve and it needs a relatively low energy to reach the maximum probability to take place the fusion process.

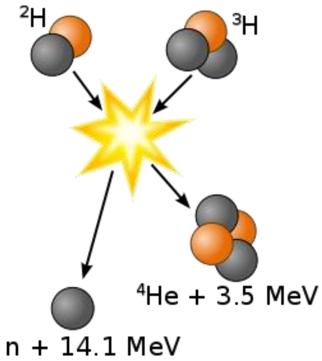

Fig. 2 – D-T fusion reaction

As a result, the future fusion power reactors will use D-T because this reaction has been identified as the most efficient for fusion devices. Moreover, D can be found plentifully on Earth; on the other hand, T is extremely rare on nature because it is radioactive with 12.3

years half-life, but can be created in another reaction using the neutrons produced in the fusion reaction:

$$n + {}^{6}_{3}Li \rightarrow {}^{4}_{2}He + T \qquad \text{(Eq. 4.2)}$$

An important number of “fusion machines” have been gradually refined along the years and the Tokamak has become de dominant concept in fusion research and multiplied around the globe. Scientists have designed the next steps called ITER and DEMO, and they will be explained in the following section.

4.2. The ITER and DEMO projects

Attempts at controlling fusion for power production follow two main experimental approaches that are being studied: the magnetic confinement and the inertial confinement. The first method uses strong magnetic fields to contain the hot plasma while the second involves compressing a small sphere containing fusion fuel to extremely high densities using strong lasers or particle beams.

Nowadays, the magnetic method is the most developed and two configurations can be used: the mirror confinement and the toroidal confinement. There are several types of toroidal confinement system; the most important are Tokamaks and Stellarators devices. As stated before, Tokamak is the dominant concept in fusion research where charged particles describe a helix trajectory along the magnetic toroidal field lines created by a series of coils evenly spaced around the torus-shaped reactor, and the poloidal field created by a system of horizontal coils outside the toroidal magnet structure. A strong electric current is induced in the plasma using a central solenoid (transformer), and this induced current also contributes to the poloidal field. In this way, the plasma is confined properly despite of the reactor works by pulses as the transformer has to be recharged.

More than 200 Tokamaks have been built around the world. The Joint European Torus (JET); in Culham, U.K., in operation since 1983, achieved the world's first controlled release of fusion power. The Tore Supra Tokamak in Cadarache holds the record for the longest plasma duration time of any Tokamak: six minutes and 30 seconds. The Japanese JT-60 achieved the highest value of fusion triple product: density, temperature and confinement time, of any device to date ($1.53 \cdot 10^{21}$ keV·s·m^{-3}). US fusion installations have reached temperatures of several hundred million degrees Celsius.

Achievements like these have led fusion science to an exciting threshold: the long sought-after plasma energy breakeven point. Breakeven describes the moment when plasmas in a fusion device release at least as much energy as is required to produce them. Plasma energy breakeven has never been achieved: the current record for energy release is held by JET, which succeeded in generating 70 percent of input power.

The next step is called ITER, a large-scale scientific experiment that includes China, the European Union, India, Japan, Korea, Russia and the United States, which will produce more power than it consumes: for 50 MW of input power, 500 MW of output power will be produced. ITER will try to prove the viability of fusion as an energy source and to collect the data necessary for the design and subsequent operation of the first electricity-producing fusion power plant. Its construction began in 2007 in Cadarache, France; and the first plasma is expected to be produced in 2020.

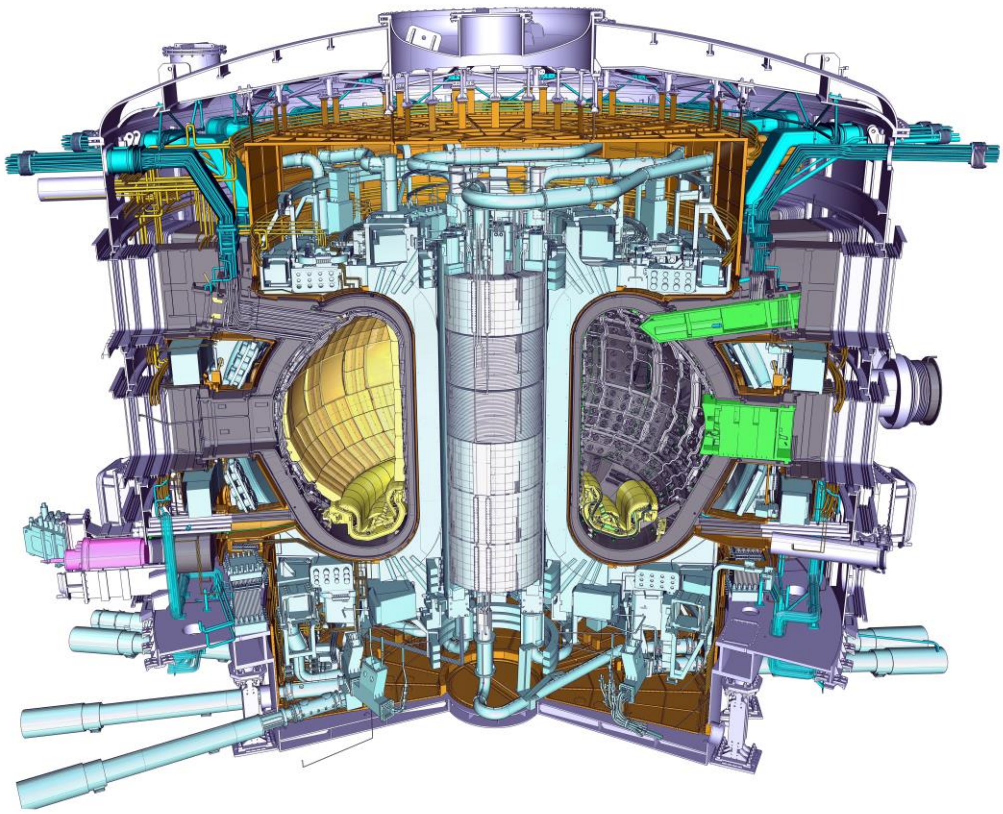

Fig. 3 – From the ITER Design Office, a detailed model of the ITER Tokamak. Image Credit: ITER Organization 2011

The main aim of ITER is:

- to produce ten times more thermal energy from fusion heating than is supplied by auxiliary heating

Moreover, ITER's secondary targets are:

- To produce a steady-state plasma which generate five times more energy than it consumes.
- To maintain a fusion pulse for up to 480 seconds.
- To develop experimental technologies needed for a fusion power plant, including superconducting magnets and RH.
- To approach to the ignition.
- To verify T breeding concepts.
- To refine neutron shield/heat conversion technology.

ITER is not an end in itself: it is the bridge toward a first plant that will demonstrate the large-scale production of electrical power and tritium fuel self-sufficiency. DEMO is this following step. To achieve this in the shortest timescale, studies have shown that aside from the operation of ITER, a parallel program of materials testing would be needed. Development of these materials is the prime purpose of the IFMIF. It's expected that the DEMO conceptual design could be complete by 2017.

5. The international fusion materials irradiation facility

As stated above, IFMIF is an international scientific research program designed to test materials for suitability for use in the fusion reactors, in particular, DEMO. This project is planned by Japan, the European Union, the United States and Russia, and managed by the International Atomic Energy Agency (IAEA).

5.1. IFMIF requirements

The main aim is to recreate the conditions that there are inside the reactor and to bombard with them the tested materials. A particle accelerator-based neutron source to produce a large neutron flux is used to guarantee this principal goal and, thus, to develop and qualify the radiation resistant and low activation for the specimens. The generated conditions are:

- 14 MeV of energy
- 10^{17} $n \cdot s \cdot m^{-2}$ of neutron flux
- A damage rate of 20 dpa/fpy (displacements per atom/full power year)

The IFMIF is made up of five different facilities: the accelerator, the target, the test, the conventional systems and the central control. In order to reproduce a reactor in continuous operation, an overall availability of 70% is required to reach accumulated damage levels around 100 dpa in a few years of operation. The availability requirements are affected for the scheduled maintenance plan for the annual campaign:

- One long maintenance period of 20 days; mainly for the target, the test modules replacement and the accelerator. The RH tasks will be carried out during this time.
- One intermediate period of 3 days for the replacement of boron nitride disks of the ion source and fast activities in the accelerator and other conventional systems.

Table 1 – Required IFMIF availability goals for different facilities

IFMIF Facilities	**Current requirements**
Tests Facility	96%
Target Facility	94%
Accelerator Facility	87%
Conventional Facilities	98%
Central Control System and Common Instr.	98%
TOTAL (product)	**75%**

The previous table has been obtained from the *Accelerator Facility RAMI Report DDD-II* [6].

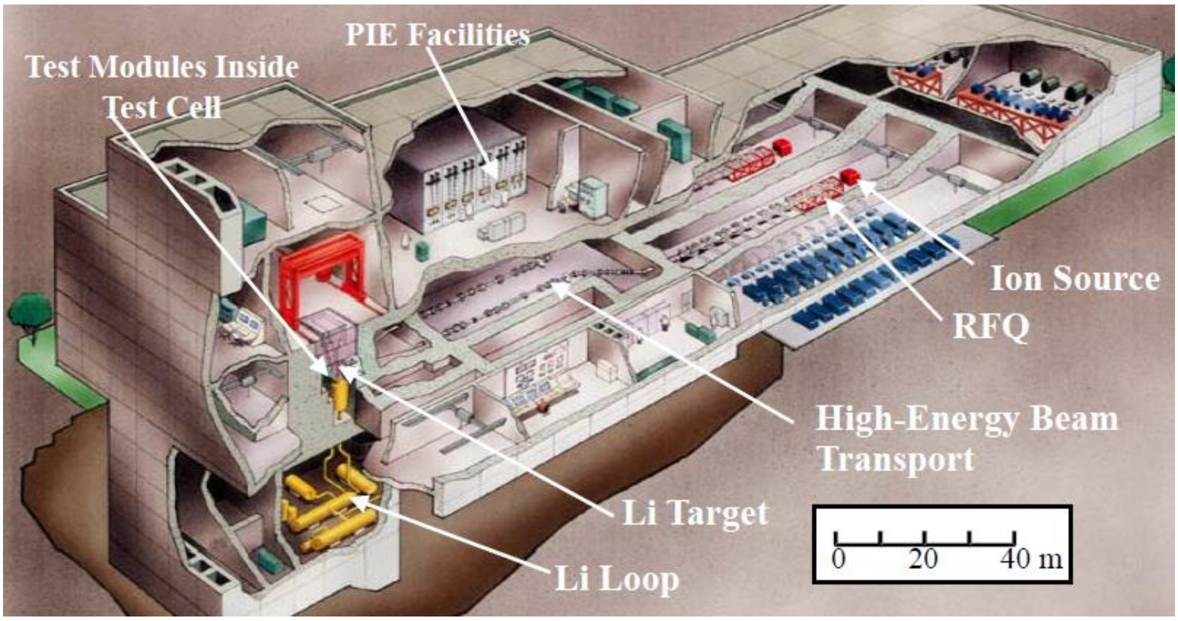

Fig. 4 – Overview of the IFMIF design, with major subsystems identified from the CDR[3]

The following is a brief description of the different facilities.

5.2. Accelerator facility

IFMIF uses two 40MeV deuteron Continuous-Wave linear accelerators; each delivers a 125mA beam current directed to a common flowing Li (lithium) target [3]. Each IFMIF accelerator is a sequence of acceleration and beam transport stages. The deuteron beam is produced and extracted from an Electron Cyclotron Resonance Ion Source (ECRIS) at 100keV. A Low Energy Beam Transport (LEBT) section guides the deuteron beam from the source to a Radio Frequency Quadrupole (RFQ). The RFQ bunches the beam and accelerates 125mA to 5MeV. The RFQ output beam is injected through a matching section called Medium Energy Beam Transport line (MEBT), which guides the beam up to the next accelerating system: Superconducting Radio Frequency Linac (SRF), composed of four cryomodules totalizing 42 superconducting cavities and 21 solenoids, bring the beam energy to 40MeV, and finally a High Energy Beam Transport line (HEBT) guides and shapes the beam to produce a rectangular and uniform footprint at the level of the lithium target. [7]

- *Injector*

It consists of the ECRIS and the LEBT. The first one generates deuterons in Continuous-Wave mode at 100 KeV working as follows: Gas (Deuterium, in this case) is injected in a chamber and it's heated up with microwave radiation. The gas is ionized and the free electrons are kept in the chamber describing helicoidal orbits by means of magnetic fields. The collisions between theses free electrons and D atoms produce more ions that can feed the continuous wave beam. The LEBT is a pair of weak focusing magnets that has to match the beam to the RFQ input needs. There is also a couple of dipoles or steerers which are optical elements used to focus the beam in the transverse directions if it deviate. [7]

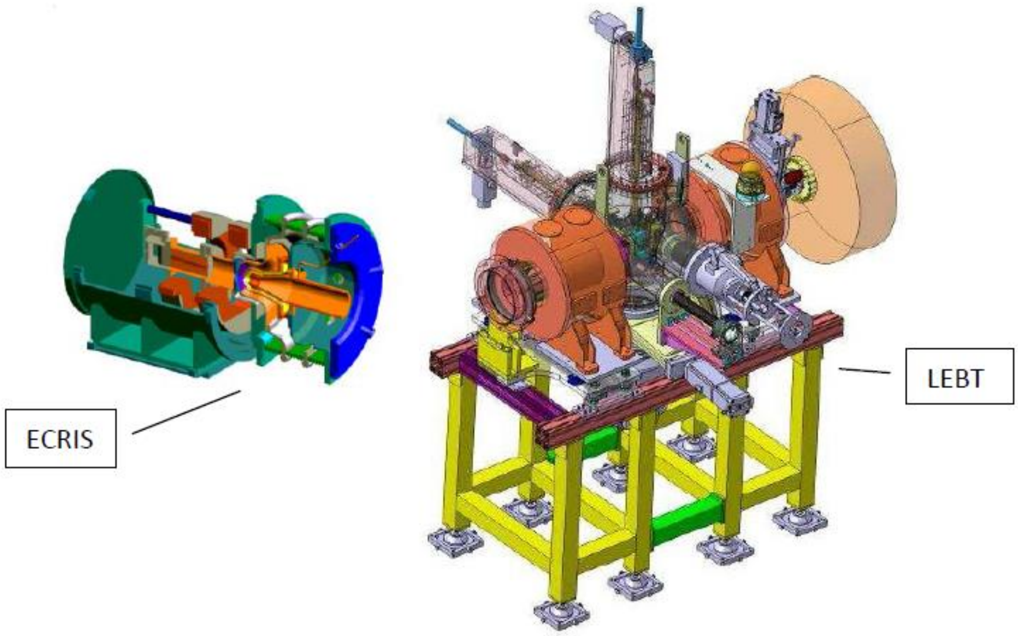

Fig. 5 – IFMIF injector sections[7]

- *Radio Frequency Quadrapole*

The beam is accelerated since 100KeV to 5MeV and bunched to reach the 175 MHz frequency required for the SRF Linear Accelerator.

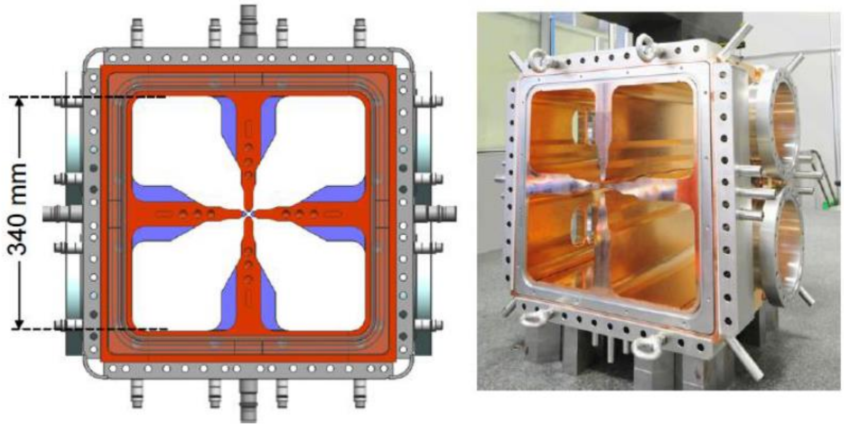

Fig. 6 – Example of Radio Frequency Quadrapole cavity[7]

- *Medium Energy Beam Transport*

  Its function will be a more accurate adaptation for the SRF linac inputs. MEBT focuses the beam in transverse using 1 triplet and 1 doublet quadrapoles and in longitudinal with 2 buncher cavities.

- *Superconducting Radio Frequency Linear Accelerator*

  This is the main part of the accelerator, where the beam is accelerated from 5 to 40 MeV. It is composed of 4 cryomodules. They focus the beam with solenoids and they accelerate it using superconducting Half Wave Resonators. A Half-wave resonator is a cavity made to match its measures with half the wavelength of the electric field in it. This way a resonance is generated and the amplitude is enhanced, and the energy associated to it (and transmitted to the particles) is much higher. The cryomodules have in total 21 solenoids and 42 resonators.

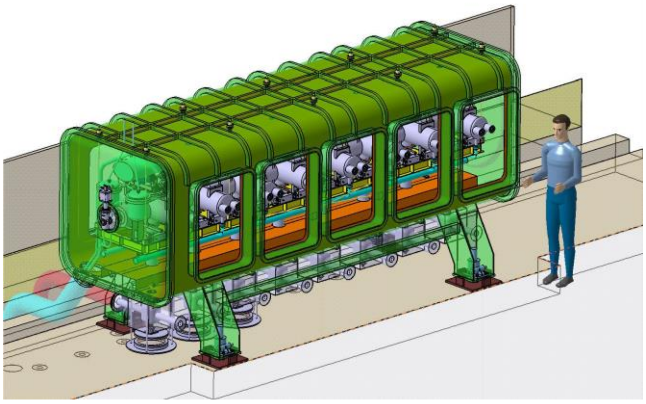

Fig. 7 – General view of an IFMIF cryomodule[7]

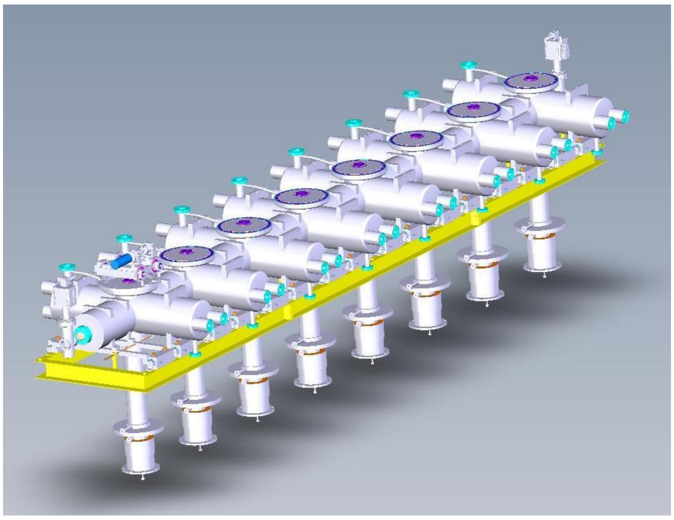

Fig. 8 – Cavities equipped with their power couplers and the superconducting solenoids[7]

- *High Energy Beam Transport*

  Finally, a HEBT line focuses the beam by means of quadrupoles and homogenizes the beam density by means of higher order multipoles, bends it by means of two dipoles and expands and matches it to the required rectangular and uniform footprint at the level of the lithium target. [7]

5.3. Target facility

The IFMIF Li target system shall be designed to have a capability of removal of 10MW heat power produced by the deuterium beams, to produce a stable Li jet with a wave amplitude less than 1mm at a speed of 10–20m/s, to control level of the impurities (T, Be-7, C, O, N) below permissible values, to have sufficient safety with respect to the Li hazard and tritium release from the Li loop and to achieve required system availability during plant lifetime. Specifically, the major function of the IFMIF Li target is to provide a stable Li jet where the accelerated deuterium beam to 40 MeV collides against. This reaction produces high energy neutrons in a range around 14MeV.The flux of neutrons reproduce a nuclear fusion energy reactor environment. The explained design follows the *Status of engineering design of liquid lithium target in IFMIF-EVEDA* [8] model.

The Li target consists of the target assembly, the Li loop, Li purification loop and the diagnostics. In addition, the RH systems will have to carry out a lot of tasks in this facility.

- *Target Assembly*

The Target Assembly (TA) consists of a flow straightener, a double-reducer nozzle, a back-plate, drain baffles and flanges. The flow straightener is provided to change turbulent flow to laminar flow. The back-plate operates under severe conditions of neutron irradiation damage (about 50dpa/fpy) and its design has been updated regularly. It's planned its replacement every 11 months using RH.

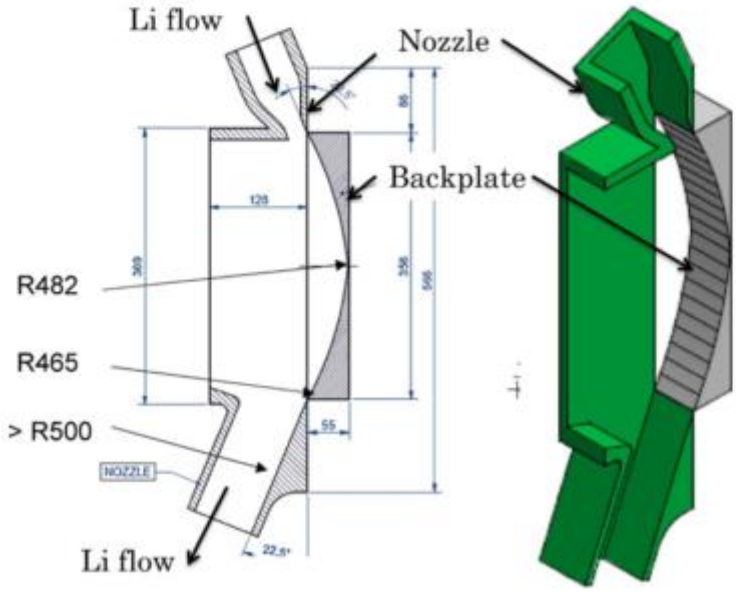

Fig. 9 – Concept of the back-plate and the nozzle[8]

- *Li main loop*

The major components of the Li main loop are a quench tank, a surge or overflow tank, a Li dump tank, an organic dump tank, an electromagnetic pump, and two heat exchangers. The total Li inventory is about 9m^3. In addition, there are a trace heating system to maintain the temperature throughout the loop above the melting point of the Li, thermal insulation layer, valves, electromagnetic flow meters, instrumentation, and connections to vacuum pump and argon gas headers. Almost all Be-7 produced by D-Li reaction, $5.02 \cdot 10^{15}$ Bq, would be deposited in the form of Be_3N_2 on most downstream parts of the heat exchanger with the lowest temperature among the main flow.

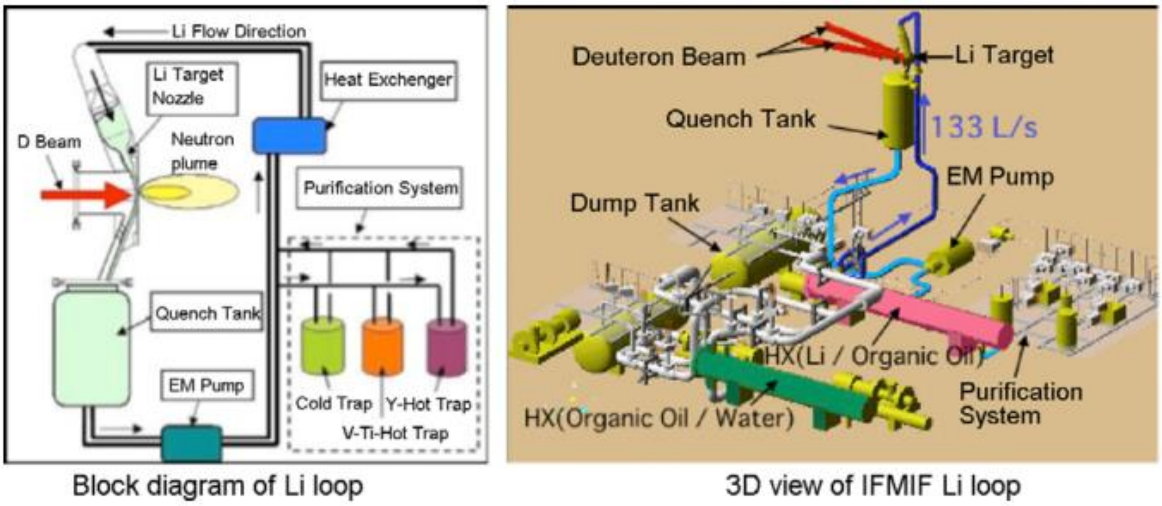

Fig. 10 – Block diagram and layout of the Li target system[8]

- *Li purification loop*

The Li purification loop consists of a cold trap and two hot traps to remove various impurities and auxiliary supporting equipment (small electromagnetic pump, flow meters, valves, trace heaters, and connections to argon/vacuum headers). The cold trap removes most of the Be-7 and oxygen, but some is expected to deposit inside the loop such as heat exchanger. Nitrogen will be removed by one of the hot trap with Titanium and Hydrogen isotopes (H, D, and T) will be removed by the other hot trap with Yttrium. Moreover, there will be an off-line and on-line impurity monitors.

- *Diagnostics*

In order to evaluate characteristics of the Li flow during operation and to control the Li target system, candidate diagnostics on surface wave characteristics, Li flow velocity, Li thickness, Li temperature and displacement of the TA and in the back-plate are considered. A fast video camera applying the Particle Image Velocity technique, ultrasonic sensors, contact-type movable sensors, thermo-couples, an infrared camera and a laser diagnostic will be used for these tasks.

- *RH system*

This system will be explained in detail in the following section. Since severe activation of the target assembly components is expected under neutron irradiation, the repair, inspection and maintenance of IFMIF target system components has to be carried out remotely. In addition, the back-plate and the target assembly are the most critical part to be maintained in the target.

5.4. Test facility

As defined in [1] and [9] the test facility is the cavity that accommodates the Li target assembly and the test modules (TMs) where the material specimens will be irradiated. Each TM is connected with TC through respective Test Module Interface Head (TMIH). Moreover, the test has to provide sufficient shielding between the TC and the non-irradiation area and a convenient access for RH tools to operate on the TM and the Li Target Assembly.

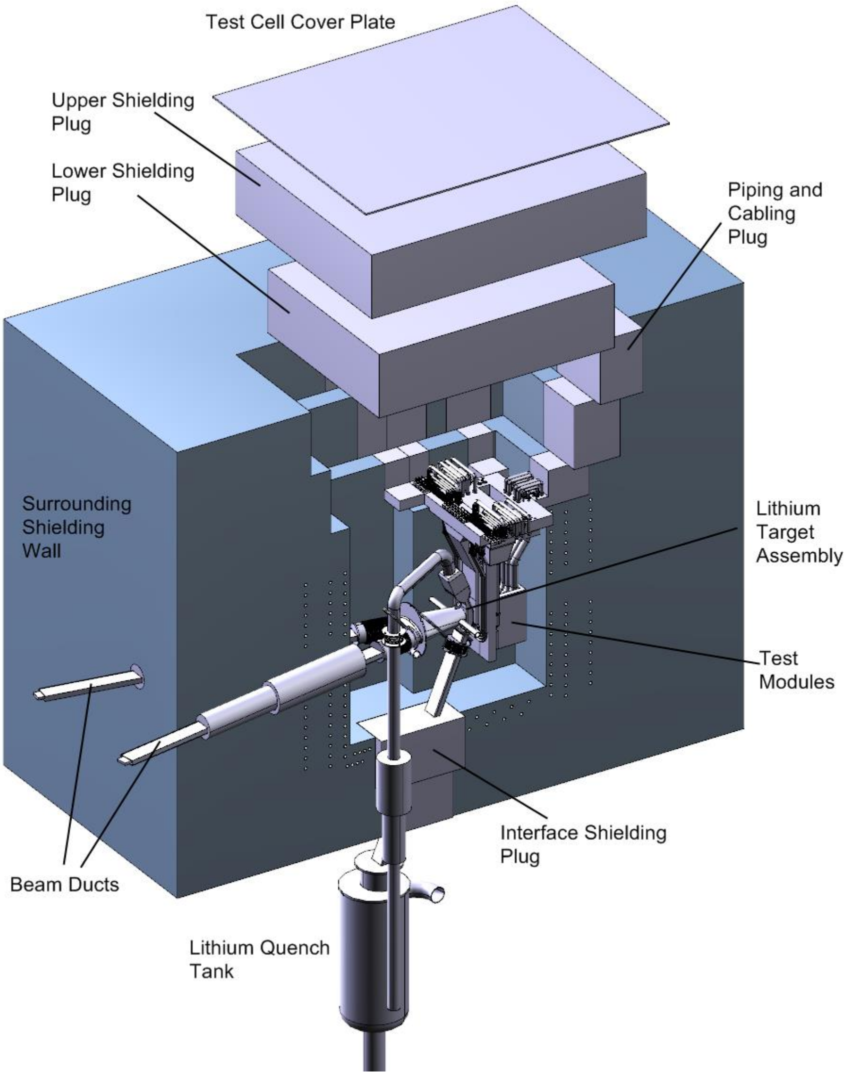

Fig. 11 – IFMIF test facility[9]

The TC will allocate the High Flux Test Module (HFTM), the Medium Flux Test module (MFTM); including the Creep Fatigue Test Module (CFTM), the Neutron Spectrum Shifter (NSS), the Tritium Release Test Module (TRTM), the Liquid Breeder Validation Module

(LBVM) and the Low Flux Test Module (LFTM)[9]. Four modules are considered in this report since the layout is constantly updated and the assembly will change every year depending on the experiment developed.

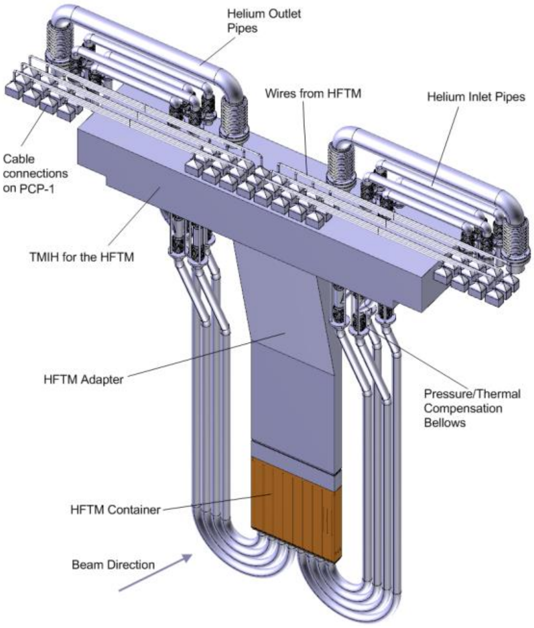

Fig. 12 – HFTM with its TMIH (Test Module Interface Head)[9]

The AC is foreseen as a closed cavity located directly at the top of the TC to accommodate all of the necessary RH tools and systems required for all of the operations, including the handling of all of the removable components. The removable components will include: all of the TMs, the target assembly, the back-plate, Top Shielding Plugs (TSPs), TC Cover Plate (TCCP) and Piping and Cabling Plugs (PCPs). According to the IFMIF CDR report[3] the Test Module Handling Cell (TMHC) is a hot cell located directly between the AC and the Post Irradiation Examination (PIE) facilities. However, the final design is not decided and, currently, the TMHC is divided into several connected cells which will be explained in the following section and it is located below the AC.

In the current TC design[9], the Li quench tank is arranged outside the TC. This is a significant change from the previous TC concepts and designs[1][2][3]. The main motivation of this configuration change is to reduce the inventory inside the TC, reduce activation of the quench tank, and provide it convenient maintainability.

5.5. Conventional facilities

These facilities are the building in which all the other and the ancillary systems will be housed. It will be possible to group their buildings in separate complexes.

Besides housing for the main process facilities, the Conventional Facilities also include other systems:

- *Heat extraction system*: needed to cool down different parts of the accelerator, the Li loop and the test.
- *Electrical power distribution system*: each facility needs a high reliability feed to operate safely and efficiently.
- *Ventilation and air conditioning*: it has to ensure air quality for all the areas where personnel accesses. Moreover, it has a radiological protection function.
- *Gas supply system*: it provides a dry inert gas.
- *Central vacuum system*: the manifold is evacuated by a series of pumps that discharge exhaust at atmospheric pressure.
- *Water system*: it is required to supply plant process and domestic uses. Separate systems are required for potable water, fire protection water and process water.
- *Radioactive waste treatment facilities*: it keeps activated pieces and liquids for the established time, until primary cooling and proceed in the convenient way in each case.
- *Neutron Monitoring*: Online neutron detection methods that were considered include; gamma thermometers, activation wires, bubble detectors, and activation counters.

5.6. Central control system and common instrumentation

The central control and common instrumentation system provides overall control and monitoring of IFMIF operation and personnel access and to assure safety. The IFMIF facilities will be controlled and operated by a hierarchical architecture in which each of the facilities will have dedicated control systems linked to the plant central control system.

The common instrumentation is made up of the radiation monitoring system, a video system, an access control system using door limit switches and keypad combinations, monitors, portable survey meters and personal dosimeters.

6. REMOTE HANDLING

6.1. Introduction

This section contains a description of what RH is, a brief list with the facilities around the world that use RH tools and the design of the RH system for the AC ant the TC inside IFMIF according to the DDD-II model [4]. In addition, the RAMI requirements for this equipment and the former FMECA considered are shown.

Firstly, it's necessary to understand the reasons which forced the use of remote handled operations.

One of the most technically challenging activities of the IFMIF facility is the maintenance and the refurbishment of its components, and among these the target system and the test modules appear to be critical since it is located in the most severe region of neutron irradiation. [10] Thus, the use of RH tasks is justified, based on:

- A frequent maintenance and replacement cycle: a long annual maintenance period of 20 days that should not affect the overall availability of IFMIF.
- The radioactive environment: the effective dose exceeds the minimum hand maintenance zone (650µSv/year) due to the gamma and beta radiation as a result of contamination and activation by elements such as Tritium, Cobalt 60, Beryllium 7…

Hence, this report will be a further contribution to the strong effort between the IFMIF community is being focused on the improvement of the RH strategy for the maintenance tasks which must be performed rapidly and with high standards of safety and reliability.

It's important to highlight that the final design of both the RH system/equipment and the maintenance procedures will have to fulfill a great number of physical characteristics because there are heavy components, a limited access due to the shielding and a high degree of component modularization.

6.2. Experience and facilities that use remote handling

The use of tools and equipment with a higher level of remotisation and automation is becoming more common in different technology and industrial fields due to the improvement of their safety and productivity. The RH equipment can be classified into three categories:

- *Transporters*: cranes, mobile robots/trolleys, telescopic transporters.

- *Teleoperators*: master-slave manipulators, servo manipulators, electro-mechanical manipulators.
- *Robotic manipulators*: industrial robots, force/haptic controlled manipulators.

The following is a brief list that shows some facilities with RH technology:

1) Fission power plants

In the context of nuclear power plants, the use of cranes and master-slave manipulators is important and they are common tools. This equipment carries out tasks in the transport of spent fuel and spent fuel casks, maintenance, rescue, inspection actions, dismantling and decontamination. In particular, master-slave manipulators have been extensively used in the nuclear industries governed by the ALARA principle for more than five decades [11].

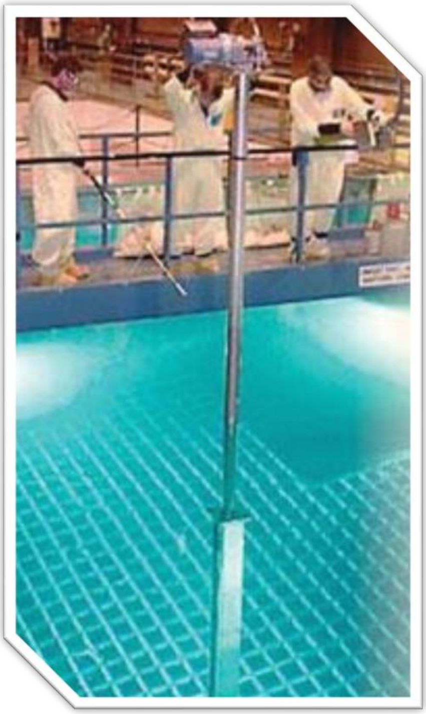

Fig. 13 – Power reactor fuel handling

Fig. 14 – Remote-controlled robot in number 1 Fukushima Daiichi power plant

2) Reprocessing plants

Once again, in these plants the RH is used in ordinary tasks and dismantling activities.

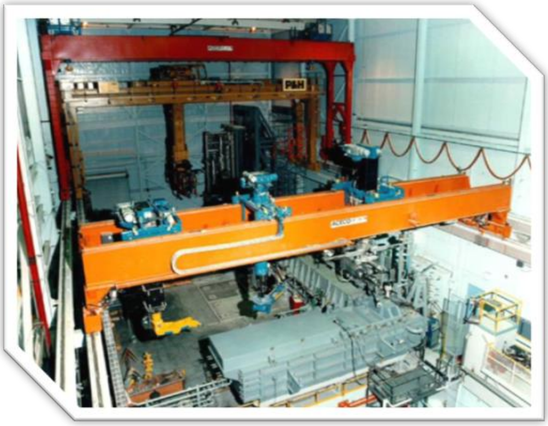

Fig. 15 – Crane used in a reprocessing plant

Fig. 16 – Remote-controlled manipulator carrier system for dismantling activities in the Wiederaufbereitungsanlage Karlsruhe (WAK) reprocessing plant which is under decommissioning

3) Fusion facilities

Many complex activated fusion machines around the world rely solely on RH to carry out maintenance and repair tasks such as JET (Joint European Torus) [12], TPX (Tokamak Physics Experiment) [13], FERF (Fusion Engineering Research Facility) [14], BPX (Burning Plasma Experiment) [15] and ITER (proposed) [16]. Moreover, the robot called Articulated Inspection Arm (AIA) conceived to unfold in a plasma chamber without loss of high vacuum and temperature conditions has been set up on Tore Supra. This experience demonstrates the possibilities of ITER to use a teleoperated arm for inspection of tokamak's vacuum vessel [17].

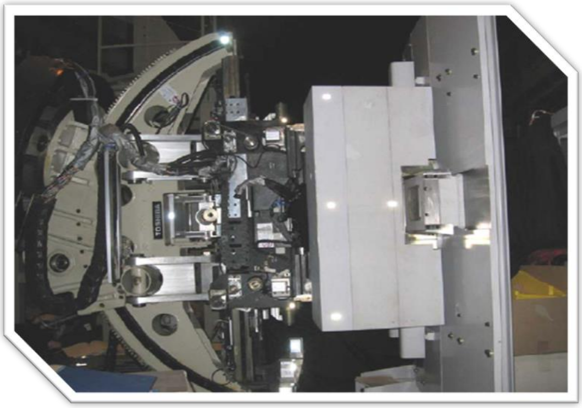

Fig. 17 – The blanket RH system for ITER

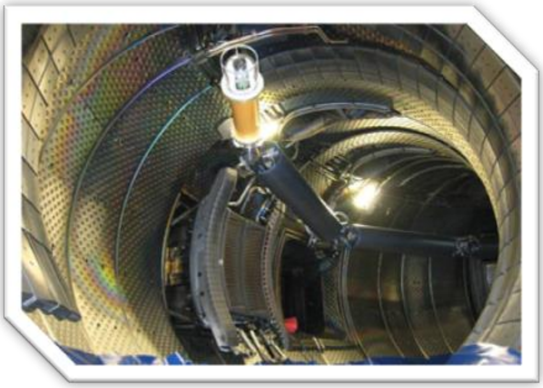

Fig. 18 – AIA in Tore Supra

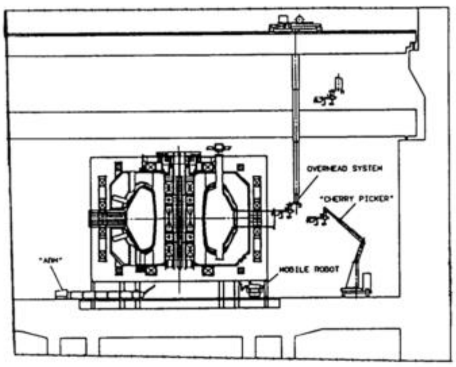

Fig. 19 – Test Cell manipulation system in BPX

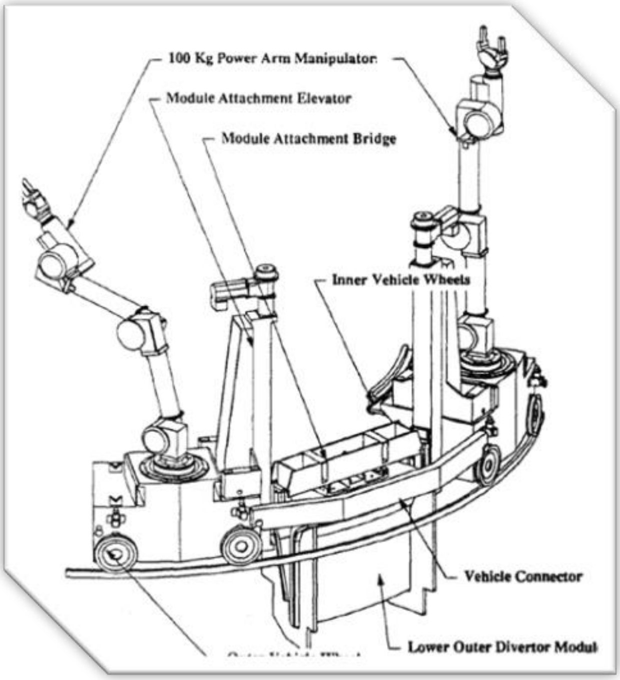

Fig. 20 – RH vehicle and manipulator in TPX

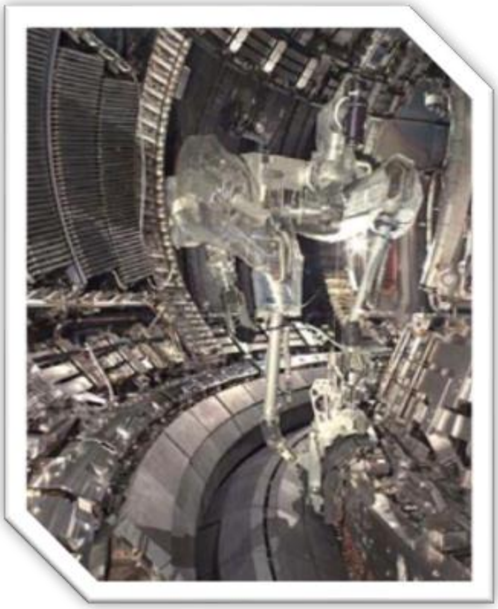

Fig. 21 – Manipulator in JET

4) Accelerator target facilities

Design for remote handling of highly activated accelerator components is becoming more prevalent as particles facilities are designed and constructed to provide ever increasing beam powers. Oak Ridge National Laboratory (ORNL) has made significant contributions to telerobotics technology and continues with active research today, for example the SNS (Spallation Neutron Source) [11]. The RIA (Rare Isotope Accelerator) will be a basic science user facility to generate high-energy, high-quality particle beams of rare isotopes for nuclear physics studies. The RIA facility will require remote maintenance capabilities in its target gallery and other associated process areas [18]. Another example of remote handling can be found at the ISOLDE facility where a robot is used to change radioactive ion beam targets. The ISOLDE facility is dedicated to the production of a large variety of radioactive ion beams. The TRIUMF-ISAC (Isotope Separator and Accelerator), the PSI (Paul Scherrer Institut) proton accelerator, the ILC (International Linear Collider) and the LANSCE IPF (Isotope Production Facility) are facilities which produce rare-isotope or proton beams and are only some more examples that use RH equipment. Also noteworthy is the RH system that will be used in the FRIB (Facility for Rare Isotopes Beams); a new national user facility for nuclear science, funded by the Department of Energy Office of Science (DOE-SC), Michigan State University (MSU), and the State of Michigan, because this equipment shares some of the IFMIF design characteristics. IFMIF would be included in this family.

Fig. 22 – Remote manipulator for the SNS in the ORNL

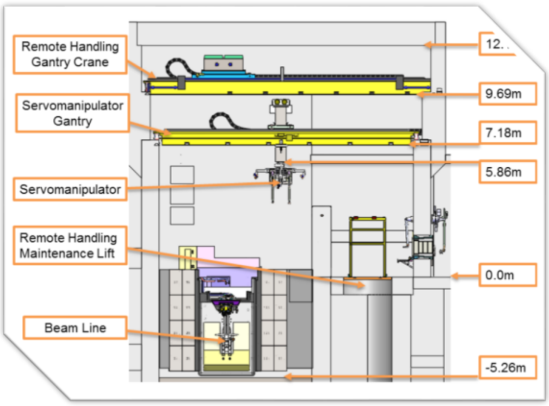

Fig. 23 – Elevation view of the FRIB target facility hot cell with remote gantry crane and servo manipulator

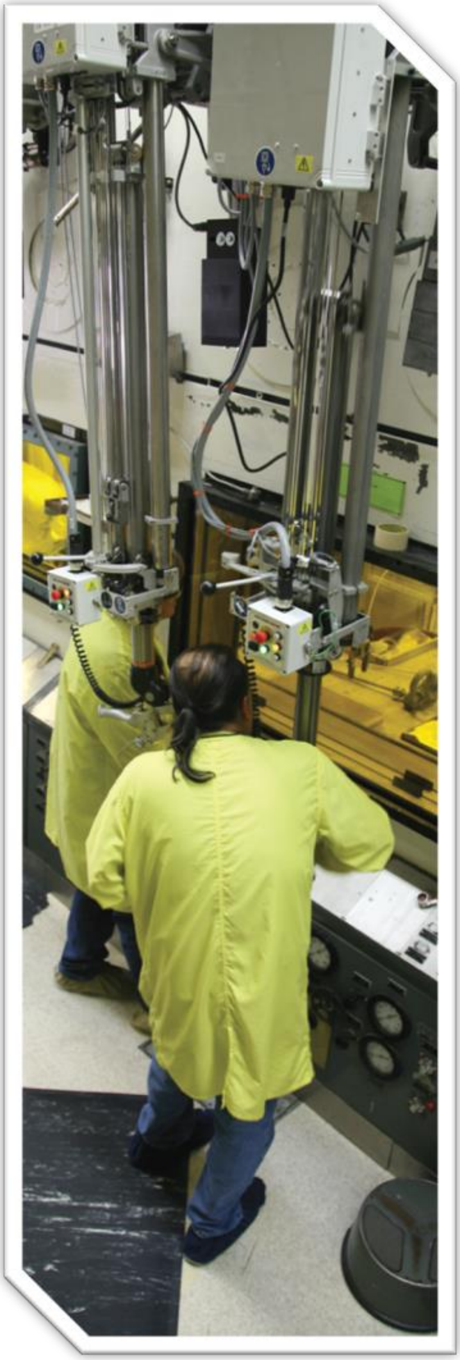

Fig. 24 – A worker unloads an IPF-irradiated target at a hot cell in LANSCE

Fig. 25 – Remote manipulator for RIA

Fig. 26 – Remote manipulator for RIA

Fig. 27 – Remote crane for ISAC-TRIUMF targets

Fig. 28 – Remote handling for the ILC positron target

5) Other fields

Lastly, the use of RH technology is not just present in the nuclear and physics field but it is common in many other industries such as the aerospace industry, security and military activities, medical treatment, underwater vehicles, etc.

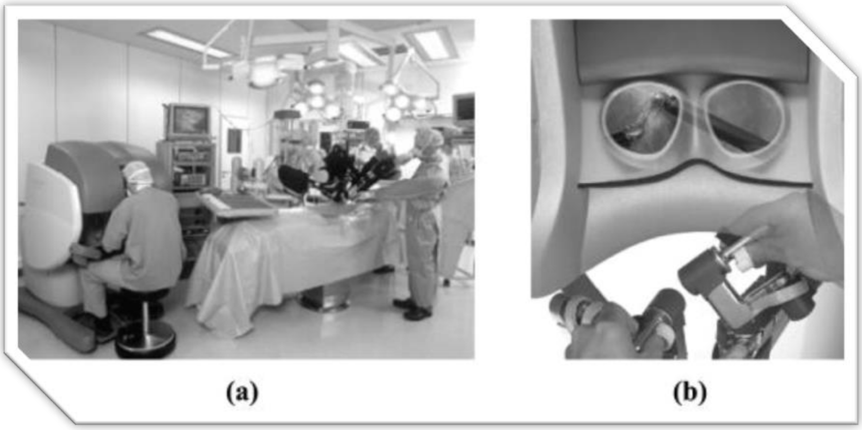

Fig. 29 – The da Vinci Surgical remote system

Fig. 30 – JASON, a remote underwater vehicle

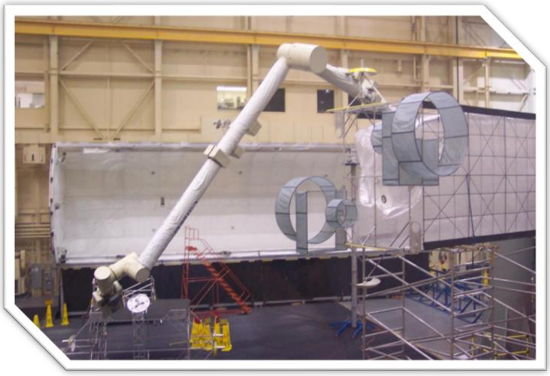

Fig. 31 – The Multi-Use Remote Manipulator Development Facility (MRMDF) designed by the NASA

6.3. Remote Handling in IFMIF

6.3.1. Basic configuration of the Test Cell, Access Cell and Test Module Handling Cell

Firstly, it is essential to explain and describe the area where the RH system remains and will carry out its tasks. As stated above, the AC is foreseen as a closed cavity located directly at the top of the TC to accommodate all of the necessary RH tools and systems required for all of the operations, including the handling of all of the removable components. When IFMIF is in operation the AC is a restricted area and a control of access will be required; on the other hand, during the maintenance period its access will be forbidden. The TMHC is a hot cell located next to the TC and under the AC and it is divided into several connected cells. Nonetheless, the design of these cells is constantly updated and the definitive one is not decided. In this report it has been accepted the configuration described in the *System Design Description Document (DDD-II) RH systems PBS 2.6.0.0.0* [4] and *System Design Description Document (DDD) Test Cell, Access Cell, and Test Module Handling Cell* [19].

The installation of the RH equipment imposes some requirements to the layout of the facility. In particular, it is an input data for the specifications of the AC, TC, TMHC and their interfaces:

- space required for the RH equipment installation and maintenance
- space required for the operations and procedures
- load capacity of the building structures

- adequate access for the assembly of the RH equipment during the construction of the facility

The cells distribution will be as shown on the next figures with these requirements and considering the functions and tasks which will be described below.

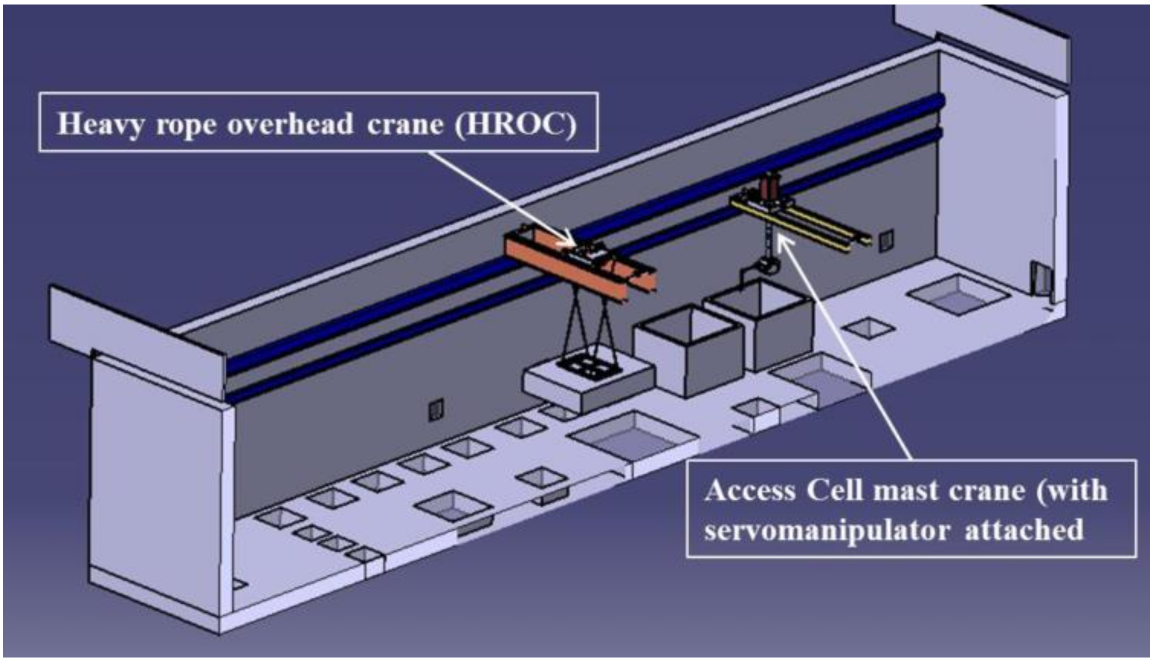

Fig. 32 – Section of Access Cell with the two cranes installed. Note that one side wall of the cell has been removed in the drawing[4]

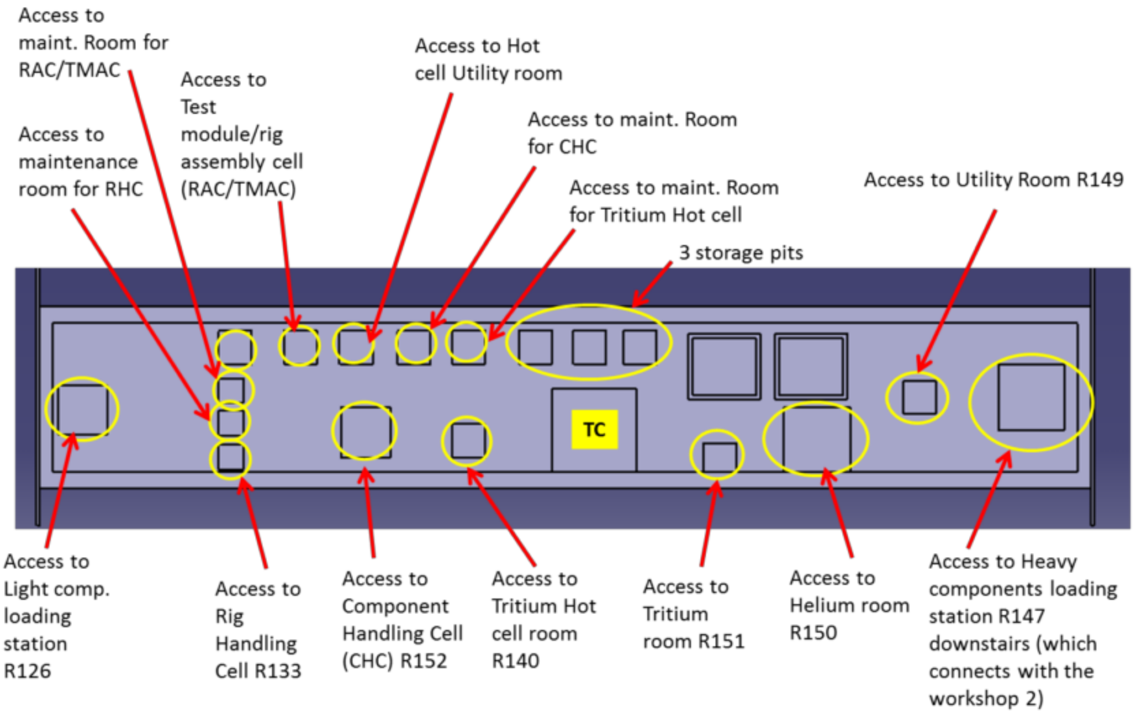

Fig. 33 – AC floor with the access to cells. Currently, the TMHC is made up of the CHC, RAC, TMAC, RHC and Tritium Hot Cell[4]

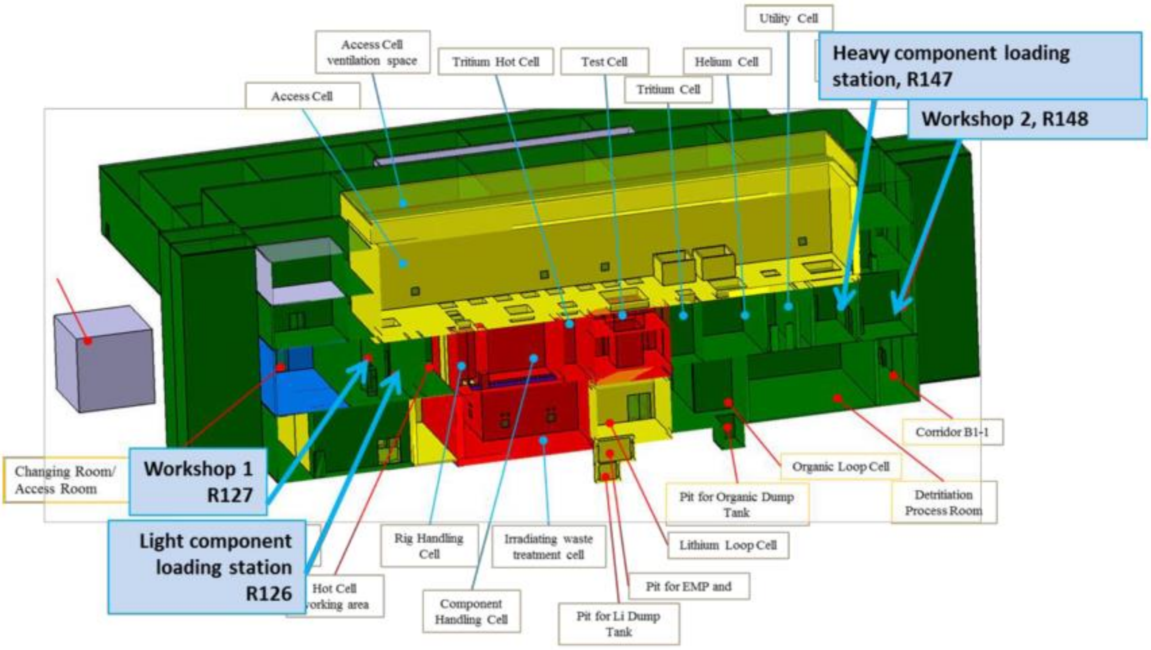

Fig. 34 – Isometric view of the current layout of Test Facilities, showing both loading stations and workshops[4]

6.3.2. RH functions

The basic functions preliminary identified are:

- F1: to remove the irradiated modules from the TC and install the new ones during the yearly scheduled maintenance period
- F2: to remove the TA from the TC and install the new one during the yearly scheduled maintenance period
- F3: to perform the required preventive maintenance tasks in the Test Facilities
- F4: to perform the curative maintenance of those cells and their components when required
- F5: to support the Test Facilities installation and commissioning phases
- F6: to support the Test Facilities decommissioning

Therefore the RH system must be able to carry out different subtasks such as welding, cutting, bolting, horizontal movements, lifting… These duties and their times will be shown in the RH FMECA (*appendix A*).

6.3.3. The components to be manipulated

The boundaries of the RH system are the systems or components related to the RH systems through a physical or a functional interface. The main boundaries of the RH systems are listed below:

- The components to be manipulated (part of them belong to the Test Facility, to the Target Facility and to the Accelerator Facility)
- The cells where the RH systems operate or have some interaction
- Auxiliary systems of the Test Facilities (electrical power supply, hydraulic power supply, etc.)
- The IFMIF central control system
- The Wastes Management System

Specifically, just the components to be manipulated will be described in this section in spite of the rest of boundaries have been taken into account when it comes to elaborate the RH FMECA (*appendix A*). Also, the RH fault tree (*appendix H*) developed in the RAMI analysis shows the potential faults associated to the power supply, the control system…

The weight, size and frequency of replacement/handling of components impose requirements for the definition of the technical specifications of the RH equipment. On the other hand, the RH systems impose some requirements on the components to be manipulated, since they must be designed RH compatible, following RH design guidelines and considering their maintainability.

The components to be handled in the AC and the TC of IFMIF are listed and briefly described and showed jointly in the figure 11:

- **TCCP (Test Cell Cover Plate)**: It is located in the AC and has a minimum frequency of maintenance of 1 time per year (due to replacement of TA and TMs). It is assumed weights less than 120 Ton.

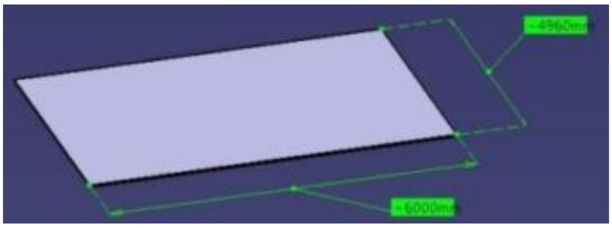

Fig. 35 – TCCP (About 6m x 4.9m x 50 mm high)[4]

- **TSP (Top Shielding Plug)**: It is located in the AC and has a minimum frequency of maintenance of 1 time per year (due to replacement of TA and TMs). It is assumed weights about 120 Ton.

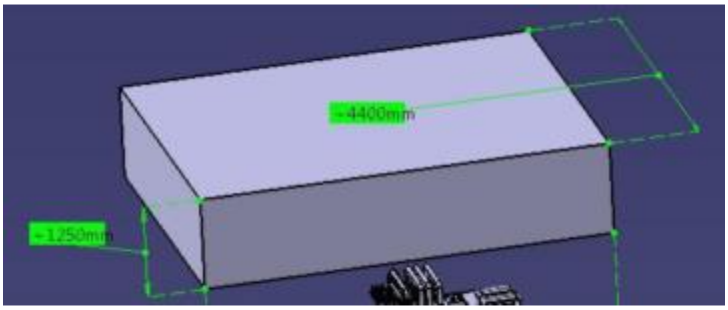

Fig. 36 – TSP (About 5.56m x 4.4m x 1.25 m high)[4]

- **LSP (Lower Shielding Plug)**: It is located in the TC and has a minimum frequency of maintenance of 1 time per year (due to replacement of TA and TMs). It is assumed weights about 80 Ton.

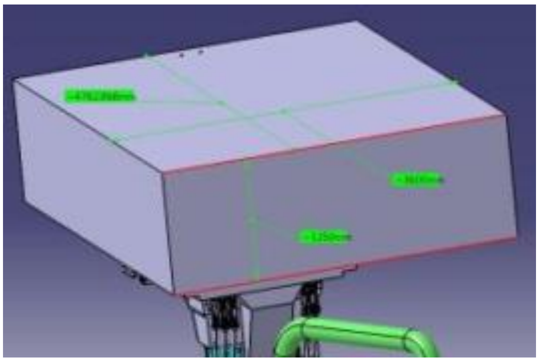

Fig. 37 – LSP (About 4.7m x 3.6 m x 1.25 m high)[4]

- **PCPs (Piping and Cabling Plug)**: They are in the TC but the first connections are in the AC. PCPs have a non-scheduled replacement (replacement due to failure). It is assumed weights about 15 Ton. There are four main configurations and some alternative.

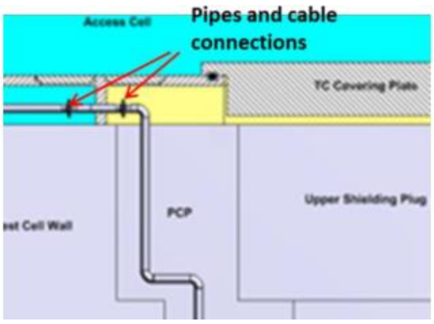

Fig. 38 – AC connections (pipes and cables coming from PCPs)[4]

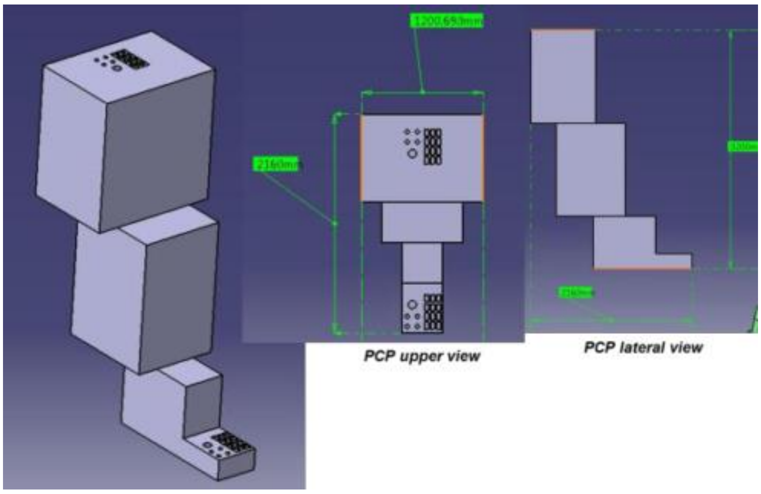

Fig. 39 – PCP-1 (PCP-4 mirror) (About 2.16m x 1.2m x 3.2m (high)[4]

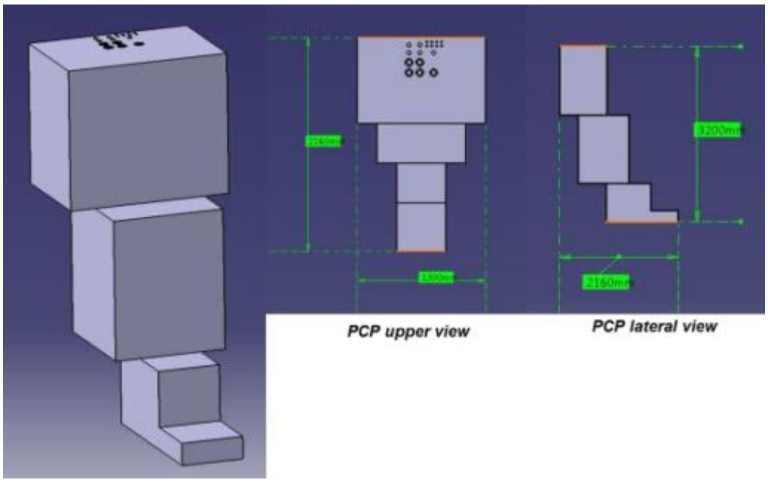

Fig. 40 – PCP-2 (PCP-5 mirror) (About 2.16m x 1.3m x 3.2m (high)[4]

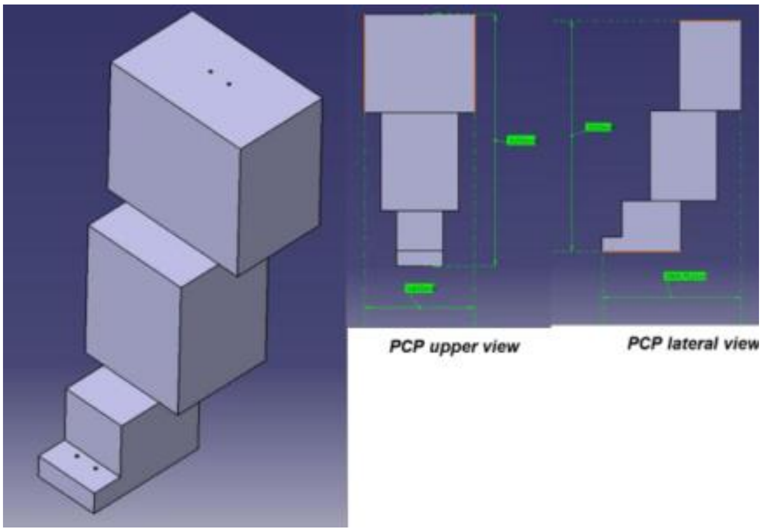

Fig. 41 – PCP-3 (About 1.94m x 1.4m x 3.2m (high)[4]

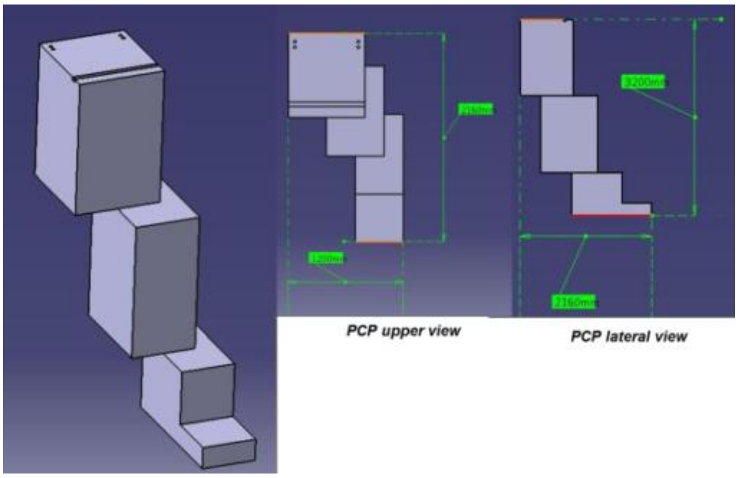

Fig. 42 – PCP-7 (About 2.16m x 1.2m x 3.2m (high)[4]

- **TMs (Test Modules)**: They are in the TC. Their weights are assumed to be around 180-500kg. As stated above, there are six different modules: the HFTM, the MFTM; including the CFTM, the NSS, the TRTM, the LBVM and the LFTM. Four modules with the HFTM specifications have been considered when it comes to develop the RAMI analysis (times and technical characteristics). The configuration of this assembly will depend on the experiment carried out every year of operation. So, they have a frequency of maintenance of 1 time per year, except the LFTM. In the present concept it seems that the overall structure of the LFTM will not be replaced once per year, only the experiments. However, it could be necessary to replace the whole module some time during the IFMIF lifetime. Each TM is connected with TC through respective TMIH where the cable and pipe jumpers are attached (it is shown in the figure 12).

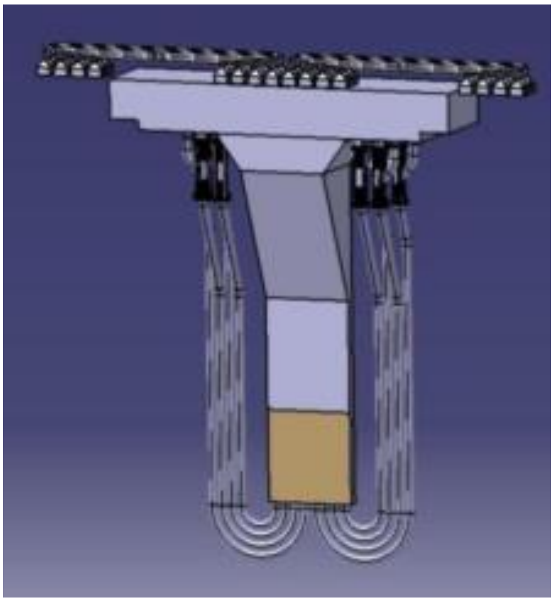

Fig. 43 – HFTM (About 1.8m wide x 2.4 m high x 0.4m depth)[4]

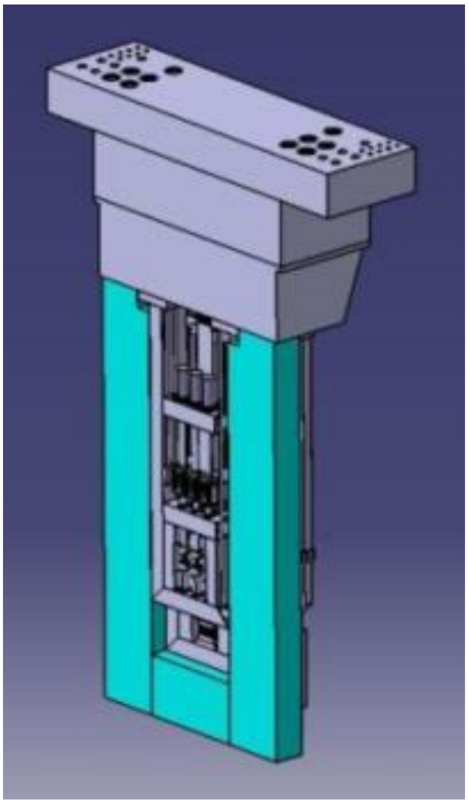

Fig. 44 – MFTM (NSS-CFTM-TRM) (1.8m wide x 0.5m depth; TMIH for 3 modules)[4]

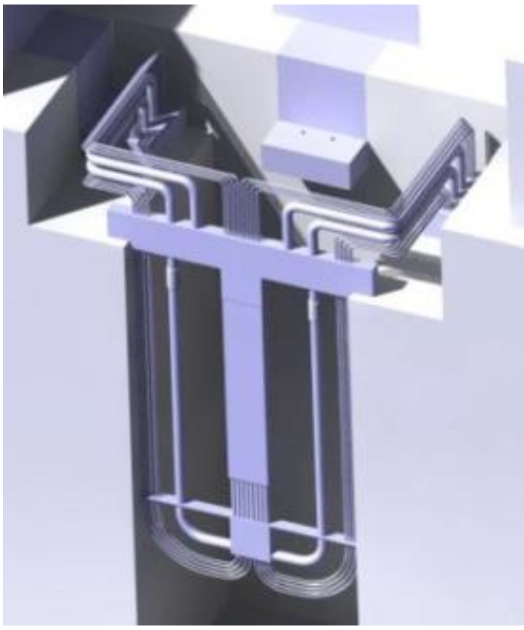

Fig. 45 – LBVM (About 2.5m wide x 0.5m depth (1.2m including upper pipes) and 3m high)[4]

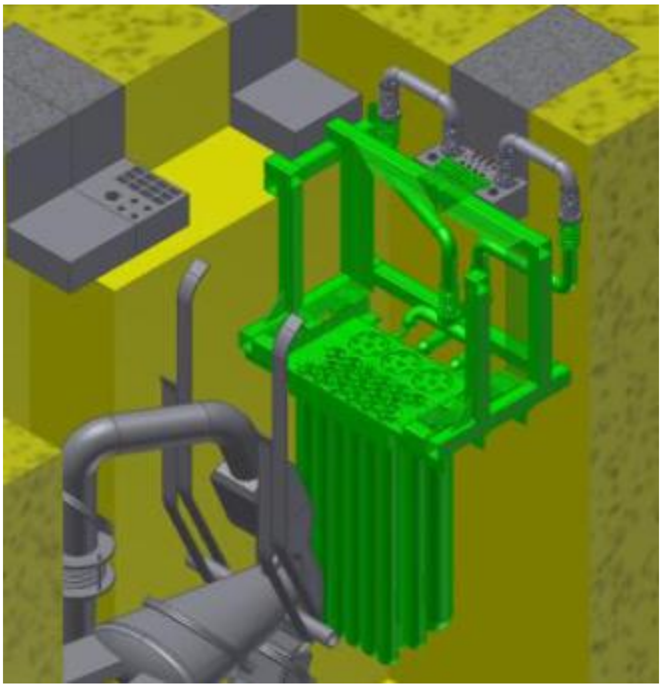

Fig. 46 – LFTM (About 2m wide, depth)[4]

- **Target assembly**: It is in the TC and has a frequency of maintenance of 1 time per year. It is assumed a weight about 1 Ton. This component needs different tasks of bolting/unbolting, welding and cutting due to its assembly that is shown in the next figure. However, it is just one of the various layouts existing; so the final one is not known.

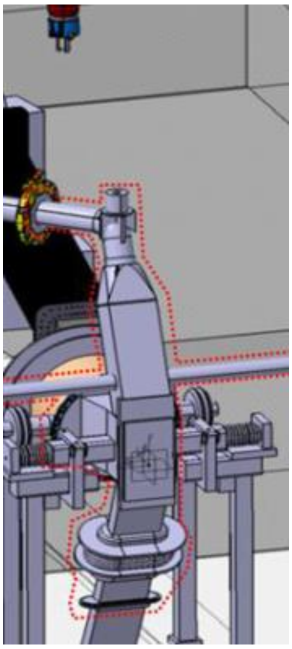

Fig. 47 – Integral Target Assembly[4]

6.3.4. System design description

In this section the RH components are detailed described.

6.3.4.1. Cranes

As shown in figure 32, there will be two cranes inside the AC:

I. ***Heavy Rope Overhead Crane (HROC)***

The HROC is a nuclear grade multi-rope double beam overhead crane. It is located in the AC to perform transfer operations of any component, specially such components weighting more than 1 Ton:

- the extraction / introduction of the TSP and LSP for the TC
- the lifting / placing the TCCP
- the location and lowering/lifting of the TMs if necessary due to rescue
- the extraction / introduction of the PCPs in case of failure
- other

This crane will be designed according to NUREG-0554 [20] for the safe handling of the loads, so that a single failure will not result in the loss of the capability of the system to safely retain the load. All the critical mechanisms must be duplicated. Using the RAMI analysis shown in this report, it will be possible to detect these critical components since the failure rates and MTTRs have been obtained from a validated FEEL database.

The most important characteristics and the technical specifications of the crane are listed in the following paragraphs:

- *Trolley*: composed of four wheels, with only two of them motorized, with motor reducer and brakes.
- *Bridge*: the mechanism of the bridged translation is formed of a motor-reducer and a cable winding drum on each side of the long walls of the building (two loops in total). Each drum has a dual coil, which in a sense coils up the cable and unwinds in the other. One wire is attached to the crane on the side facing the mechanism and the other, through a forwarding pulley located in the opposite side of the AC, is fastened on the opposite side of the crane. A tensioning system on each loop keeps the cable

rigid to prevent the crane swings in the case the cables are slightly loose. Thus, this mechanism allows the maintenance and the recovery and rescue of the crane in case of failure.

- *Degrees of freedom*: there are 6; lifting, trolley, longitudinal, vertical axis rotation of the load and, two more degrees given by the auxiliary hoist lifting and transversal displacement.

- *Working speeds*: high precision vector control inverters shall be used:

    - Main hoist, lifting, full load: 0.0 m/min to 3 m/min.

    - Auxiliary hoist: lifting, full load: 0 m/min to 7 m/min. Transversal: 0 m/min to 2 m/min.

    - Trolley speed: 0.01m/min to 10 m/min.

    - Crane translation speed: 0.01m/min to 10 m/min.

    - Rotation speed: 0.25 rpm.

- *Weight of the crane*: 60-75 Ton

- *Estimation of cost*: 6M€ - 8M€

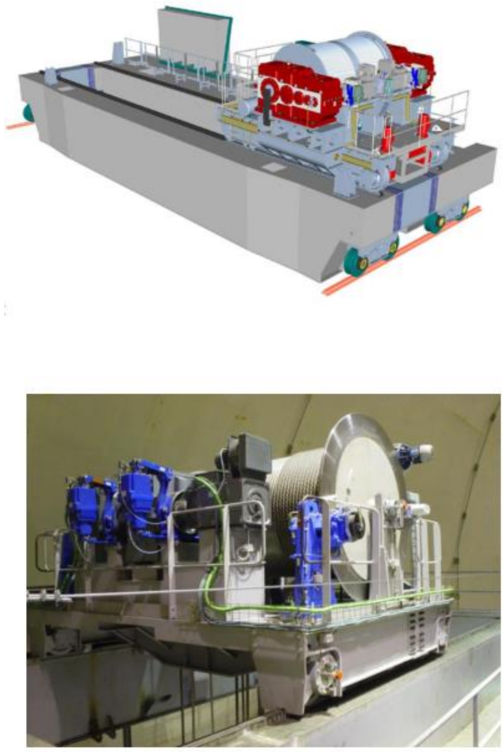

Fig. 48 – Double beam overhead heavy cranes similar to the HROC proposed for AC of IFMIF[4]

II. *Access Cell Mast Crane (ACMC)*

The ACMC will be a nuclear grade double beam overhead crane equipped with a telescopic mast. It will be installed in the AC to support and locate the Combined Manipulator System (CMS) at the correct point in the AC and therefore allowing the RH operations carried out by that servomanipulator. A Mast Grapple (MG) for vertical handling of components up to 1 ton will be also installed at the end of the telescopic mast.

The crane may be equipped with an Auxiliary Hoist of ~3 Ton load. The operations performed by this crane are among others:

- lifting of the TMs
- transfer the irradiated TMs from the TC to another cell
- transfer any other component weighting less than 1 ton
- the TA will also be manipulated by the ACMC.

The most important characteristics and the technical specifications of the crane, designed according to NUREG-0554 [20] too, are listed in the following paragraphs:

- *Trolley*: ~3 Ton (it is the approximate load supported by the trolley)
- *Telescopic mast (without any servomanipulator attached)*: 1500 kg (1000 for the load and 500 for the servomanipulator)
- *Degrees of freedom*: there are 4; trolley, longitudinal, telescopic mast lifting and rotation of the telescopic mast. Three extra for the MG (2 slight tilting and gripping). In addition, the servomanipulator.
- *Working speeds*:
  - Telescopic mas lifting, full load: 0.05m/min to 10m/min
  - Trolley speed: 0.01m/min to 20m/min
  - Crane translation speed: 0.01m/min to 20m/min
- *Weight of the crane*: 5-10 Ton
- *Estimation of cost*: 1.5M€ - 2M€

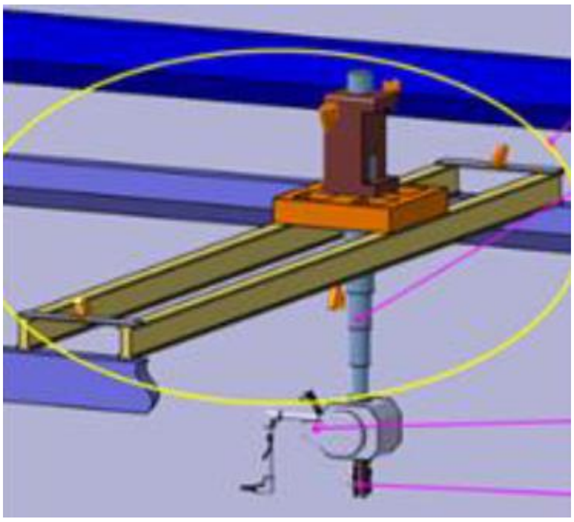

Fig. 49 – CATIA drawing of the ACMC proposed[4]

6.3.4.2. Servomanipulators

Servomanipulator, called CMS, is the piece of RH equipment to perform the “delicate” and accurate operations on the components in the TC and in the AC, mostly connection and disconnection of flanges, pipes and cables in the TMs and other RH operations for the TA. Also some transportation operations on light components can be performed by the servomanipulators.

As previously stated, this component will be fixed on a telescopic mast of the ACMC in the present configuration and it is foreseen that a MG will be attached to the bottom of the pole in order to grasp, transport, install and remove the TMs and other components weighting less than 1 Ton.

I. Combined manipulator system (CMS)

CMS is a rad-hard force-reflecting master-slave servomanipulator.

- *Degrees of freedom*: 6 + gripper
- *Load capacity*: 100 kg at full extension of arm and continuous work.
- *Working speed*: Speed of gripper <0.1mm/s to 0.5m/s
- *Estimation of cost*: 1.1M€

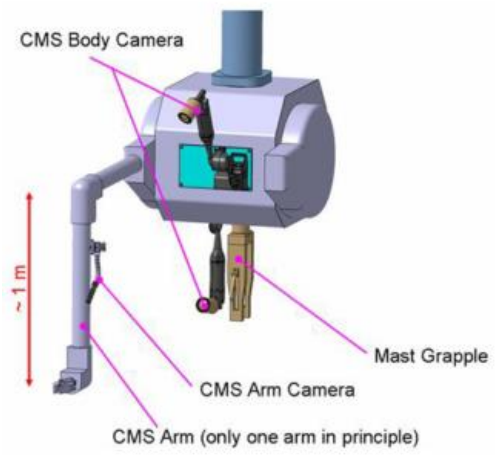

Fig. 50 – CMS attached to the ACMC crane[4]

II. Mast Grapple (MG)

MG is a rad-hard joint and gripper.

- *Degrees of freedom*: 2 + gripper
- *Load capacity*: 1 Ton
- *Working speeds*:
  - Rotation: ~0 to 0.25 rpm
  - Slight wrist pan and tilt: <0.05º/s
- *Estimation of cost*: ~0.1 - 0.2 M€

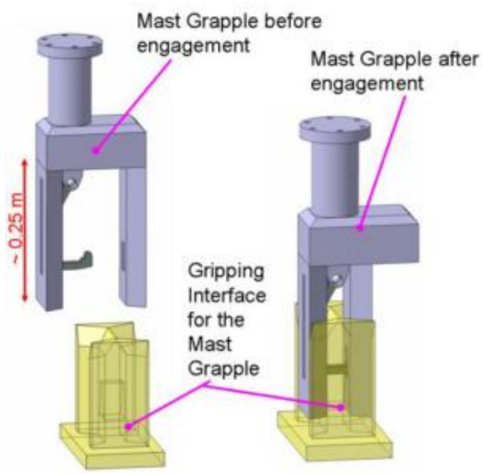

Fig. 51 – MG attached to the bottom of the Telescopic Mast[4]

6.3.4.3. Tools

Tools are instruments or devices held on the RH equipment, particularly on the servomanipulators, and used to catch, fasten, lift, or change something. These components are required in tasks of cutting, welding, bolting… A preliminary selection of the tools is defined below:

I. Frame spreader

Frame to grasp, lift and transfer some components of the TC (load capacity ~3 Ton). Each frame shall be used to lift and transfer the respective component or a similar size component.

Fig. 52 – Frame spreader layout[4]

II. Large Bolting Wrench

Bolt or unbolt the large bolts; for example those are in the vessel covers or, perhaps, one big central bolt can be used for the electrical multiconnectors at top of the TMIH too. It would have a length <~400mm and a torque up to 10000 N·m.

Fig. 53 – Modified-commercial pneumatic bolting wrench[4]

III. Small Bolting Wrench

Bolt and unbolt pipe flange bolts, electrical connectors, quick disconnection system… It’s important in TMs and target assembly removal. Two types of bolting wrenches are needed, one for the bolts having good access, usually vertical axis bolts, and angular bolting tool for bolts without wide access. They have a weight of ~20kg and a length of 400mm.

Fig. 54 – LEFT: Direct Small Bolting Tool and RIGHT: Angular Small Bolting Tool[4]

IV. Universal Cutting Tool

It will be a cutting laser or equivalent proper means, supported on a gripping interface, probably the MG. This instrument will cut the lower and upper part of the HFTM container, pipes, cables…

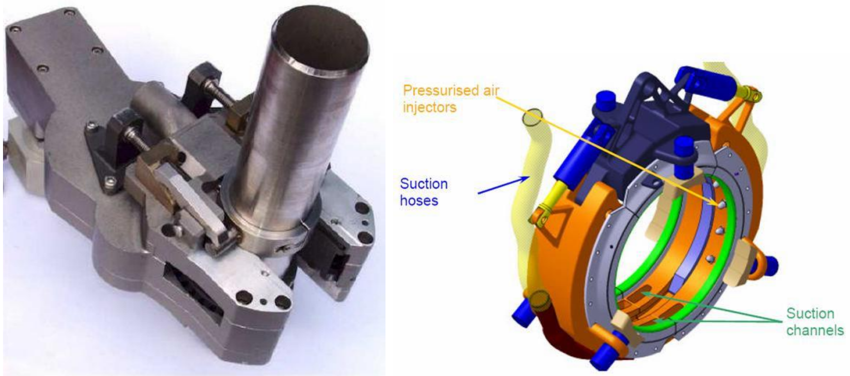

Fig. 55 – Universal cutting tool LEFT: commercial model and RIGHT: drawing[4]

V. Butt Welding Tool

This instrument will weld pipes, covers…

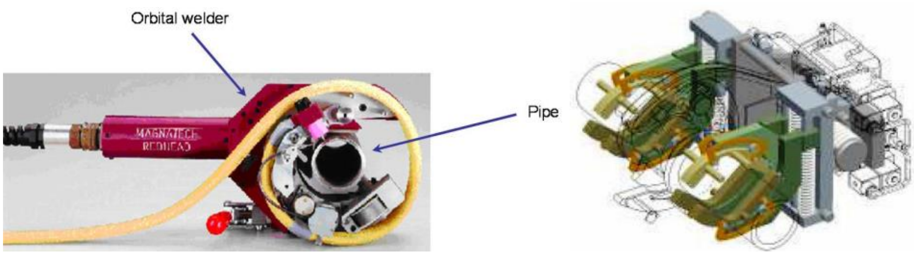

Fig. 56 – Butt welding tool LEFT: commercial model and RIGHT: drawing[4]

VI. Welding tool for straight weldings

This instrument will weld the HFTM container with HFTM attachment adapter and the HFTM Attachment Adapter with the TMIH.

6.3.4.4. Auxiliary tools

Auxiliary Tools are defined as elements that contribute to the RH operations but they are not exactly neither tools nor equipment. They are classified in four categories:

- *Tool Box(es)*: A tool box is a tray to allow transportation of certain set of tools planned to perform certain defined series of operations at the same location. For example a tool box may contain the tools for (dis)connection/unbolt the multi connectors at top of the TMs. The Tool Box should have a Lifting Interface compatible with the equipment in charge of its transportation.

- *Specimen Container(s)*: for irradiated modules or other components. These instruments were common in a former design when there were transporters. The transporters were pieces of equipment in the test facilities of IFMIF aimed for the onfloor transfer of components between rooms. In the current design, perhaps just one transporter and TM containers will be used; however, this concept is constantly updated and they does not appear in this project.

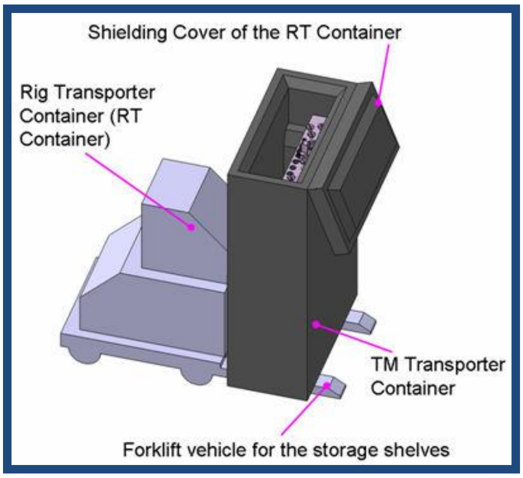

Fig. 57 – Old design of a TM transporter and container[4]

- *HFTM Shielded Support Mechanism*: It's the support where the HFTM will be disassembled.

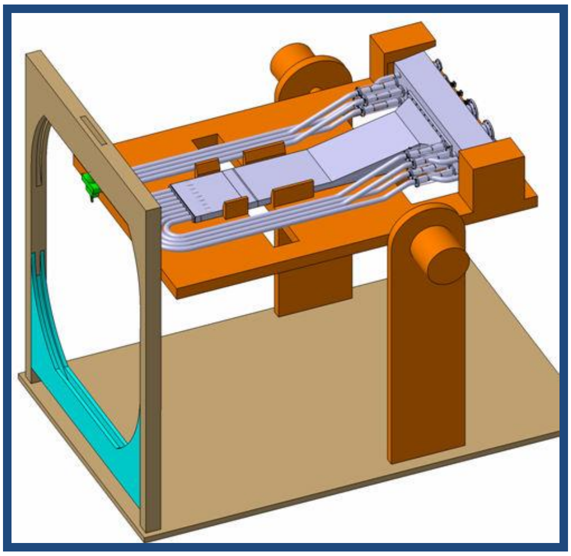

Fig. 58 – HFTM Shielded Support Mechanism[4]

- *AC Tool Box Storage Shelf and TMHC Tool Box Storage Shelf*

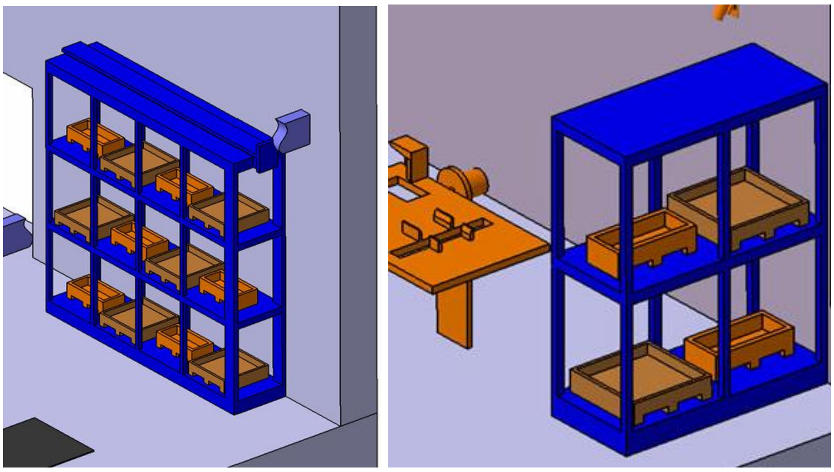

Fig. 59 – LEFT: AC tool box storage shelf and RIGHT: TMHC tool box storage shelf[4]

6.3.4.5. Viewing and illumination systems

Viewing and illumination has to be totally integrated with the building layout, the requirements of the RH equipment and tools, the shadows and vision barriers from the components, accessibility, (dis)assembling procedures, the degree of visual detail required for the particular procedure, and the supports in the building for the cameras and illumination.

Two top systems of viewing and illumination have been proposed:

I. Access Cell viewing and illumination system

It is composed of the HROC and ACMC crane-mounted viewing and illumination system: aimed for vision of the particular area where the HROC or ACMC are working on; and the AC wall-fixed viewing and illumination system, intended for general view of the working area with independence of the location of the cranes.

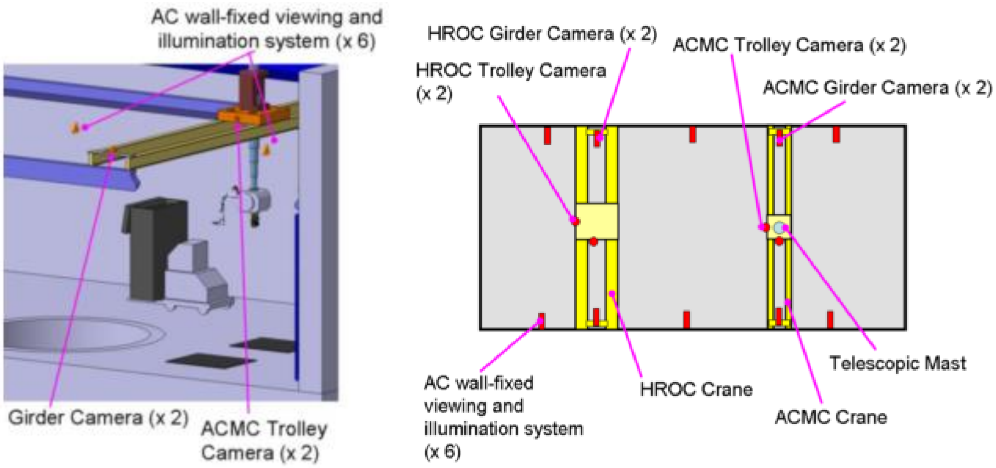

Fig. 60 – LEFT: position of some of the cameras in the ACMC and RIGHT: position of the cameras in the AC[4]

II. Portable viewing and illumination system

Composed of easily movable cameras and lights located on supports that can be grasped by the servomanipulators for transport and location where needed. One application of the Portable Cameras is the viewing and illumination of the operations inside the Test Cell. The location of the Portable Cameras must be planned and predefined before performing the operations. The Portable Cameras shall have a gripping interface (different from the attachment camera-floor fitting) to allow grasping of the camera by the servomanipulator.

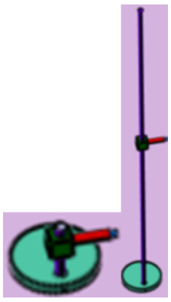

Fig. 61 – Portable viewing and illumination system concept[4]

6.3.5. RH RAMI requirements

The RH systems are conceived and designed to fulfill the plant availability according to the RAMI studies but it must be checked. The first approach was shown in the DDD-II phase, in the *Test facility RAMI Report* [21]. All the same, new results have been obtained by this research project including the HRA and they will be integrated into the design for DDD-III phase.

Two types of RAMI analyses are being performed for the RH systems regarding:

- *RH activities during scheduled maintenance plan*: a long annual maintenance period of 20 days that should not affect the overall availability of IFMIF. The main RH operations involved are the removal of the TA and the irradiated TMs from the TC, the installation of the new TMs and the new or refurbished Target Assembly, and also other preventive maintenance tasks in the TC (inspection, cables, pipes, instrumentation, etc.). In addition, the TCCP, the TSP and the LSP have to be removed and installed too. This analysis has been developed using the RH FMECA which is described below. The availability allocation for the long maintenance period is not determinate exactly but must be one so that the RH activities are achieved within the expected time (480 h) [21].

- *RH activities during irradiation*: failure inside the TC that makes stop the plant and leads to curative maintenance operations inside the TC. The RAMI analysis consists on the study of main curative maintenance scenarios:

  - ✓ 115h to replace a module
  - ✓ 160h to replace the TA
  - ✓ 504h to replace a PCP

  The availability allocation for these curative interventions is 99.1%.

In summary and as with all IFMIF facilities, RH equipment must be designed for high reliability because downtime and MTTR of the RH system implies a loss of irradiation time in this factory of neutrons.

6.3.6. First RH FMECA

A preliminary RH RAMI FMECA was performed to study the possible failures of the RH systems and the consequences. Based on this initial step, a new FMECA has been developed that includes the human factor (with the HFEs and their associated failure rates) and the components failure rates. The *Appendix A* shows this final FMECA model which has been deployed to carry out the availability analysis for the cases described in the previous section.

Nonetheless, the following list is a brief explanation about the significant aspects which shape this first RH FMECA and it has remained unchanged throughout the process.

- *Components*: the RH FMECA is divided in the components to be manipulated: TCCP, TSP, LSP, PCPs, TMs and TA
- *Tasks*: the activities carried out by the RH system for each component; liftings, releasings, horizontal movements, weldings, connections…
- *Potential failure modes and their causes*: they are the most important aspect in these analyses since it is the troubleshooting step.
- *Effects*: consequences of the potential failure modes
- *Scenarios and times*: there are the best possible scenario and the worst for each potential failure mode and they have an associated downtime depending on the refurbishment of the effects. These downtimes are estimated using *Events* which are the activities and tasks that solve the failure. Scenarios and Events are described in the following tables. Some values have changed and are updated in the final FMECA (*Appendix A*).

Table 2 – RH Failure Scenarios

	Scenario	Description/Justification	downtime (h)
1	Drop of TA in AC (1)	Without rupture of piping/elements inside AC	60
2	Drop of TA in AC (2)	With rupture of piping/elements inside AC	564
3	Drop of TA in TC (1)	Without modules inside the TC	60
4	Drop of TA in TC (2)	With modules inside the TC	2220
5	Drop of module in AC (1)	Without rupture of piping/elements inside AC	60
6	Drop of module in AC (2)	With rupture of piping/elements inside AC	564
7	Drop of module in TC (1)	With modules inside the TC	2220
8	Drop of TC cover in AC (1)	Without rupture of piping/elements inside AC	336

9	Drop of TC cover in AC (2)	With rupture of piping/elements inside AC	504
10	Drop of TC cover in TC	With rupture of TSP	130
11	Drop of TSP in AC (1)	Without rupture of piping/elements inside AC	130
12	Drop of TSP in AC (2)	With rupture of piping/elements inside AC	802
13	Drop of TSP in TC	With rupture of LSP	526
14	Drop of LSP or PCP in AC (1)	Without rupture of piping/elements inside AC	526
15	Drop of LSP or PCP in AC (2)	With rupture of piping/elements inside AC	862
16	Drop of LSP or PCP in TC	With rupture of all piping, modules and TA	2182
17	Heavy Crane curative maintenance (1)	minor maintenance (no rescue)	22
18	Heavy Crane curative maintenance (2) AC	Major maintenance (with rescue)	46
19	Heavy Crane curative maintenance (3) TC	Major maintenance (with rescue)	70
20	Small Crane curative maintenance (1)	Minor maintenance	22
21	Small Crane curative maintenance (2) AC	Major maintenance	46
22	Small Crane curative maintenance (2) TC	Major maintenance	70
23	AC curative maintenance (1)	Only repair	17
24	AC curative maintenance (2)	Repair + cleaning	353
25	TC curative maintenance (1)	Only repair	22
26	TC curative maintenance (2)	Repair + cleaning	521
27	Arm robot curative maintenance (1)	Safety position and replacement of device	14
28	Arm robot curative maintenance (2)	Safety position and major maintenance (rescue from TC)	62
29	Arm robot rescue in AC	location (worst in AC)	36
30	Arm robot rescue in TC	location (worst in TC)	60
31	Reload of TA and modules	Full long maintenance period	480
32	Removal of an element in Worst Place AC	Rescue of an element fallen from the RH AC	5
33	Removal of an element in Worst place TC	Rescue of an element fallen from the RH TC	10

Table 3 – RH Failure Events

	Events	Downtime formula	Downtime (h)
1	New PCP	see Garching 2012	504
2	New LSP	approx to PCP	504
3	New TC cover (iron)	deliver (7 days) + Access (24)	192
4	New TC cover (concrete)	cut (24) +weld (12h)+ wait (48) + access (24	108
5	New TSP	approx to TC cover (concrete)	108
6	New TA	details (24h) + access (24h)	48
7	Removal of all modules and TA	20days (maintenance plan)	480
8	Cleanning event inside TC (1)	Engineering Criteria (3 weeks)	504
9	Cleanning event inside TC (2)	3 months (RAMI report 2012)	2160
10	Cleanning event inside AC (1)	Engineering Criteria (2 weeks)	336
11	Cleanning event inside AC (2)	Engineering Criteria (3 weeks)	504
12	Rescue Heavy Crane Worst Place AC	Engineering Criteria	24
13	Rescue Heavy Crane Worst Place TC	Engineering Criteria	48
14	Rescue Light Crane Worst Place AC	Engineering Criteria	24
15	Rescue Light Crane Worst Place TC	Engineering Criteria	48
16	Repair Heavy Crane in safety position	Engineering Criteria	10
17	Repair Light Crane in safety position	Engineering Criteria	10
18	Removal of robot arm tool in safety position	Engineering Criteria	2
19	Removal of an element in Worst Place AC	Engineering Criteria	5
20	Removal of an element in Worst place TC	Engineering Criteria	10
21	Maintenance of Crane following a repair	Engineering Criteria	12

- *Components directly involved*: it refers to the components that can be damaged
- *Detection*: it refers to detection devices: visual channel, alarms…

Module (generic) handling ← Component

SUPPOSITION B: The welding operations inside the TC are only foreseen in the Target Assembly (TA) maintenance operations. However, they are described in this FMEA in case they are needed.

← Tasks

Disconnect Pipes	Connect Pipes	Welding Operations	Unwelding operations	Disconnect Cables	Connect Cables	Lift module from TC	Release module to TC	Transport module: TMAC /TC/CHC	Release module in CHC	Lift module from TMAC	Potential failure mode	Cause	Code	Effect	Scenario (Best)	Scenario (Worst)	downtime (Best) (h)	downtime (Worst) (h)	Components directly involved	Detection
											Crash between Heavy crane and light crane	Combination of failures: Defective control system (limit switches failure)+ Human failure in the application of a procedure. THERP		Drop of load of both cranes. Damage to TC or AC structure. Damage to the Connections and piping. Activated elements dispersion.	6	7	564	2220	Heavy crane, light crane, modules, lifting elements (hook, cables..), light crane, pipes and cables where hited.	Visual channel, load alarm, Pressure drop if damage in piping. Possible loss of signal channels.
											Drop of load due to cable/hook failure	Defective cables or hook.		Rupture or creep of the module. Damage to TC structure. Damage to the Connections and piping. Activated elements dispersion.	6	7	564	2220	Module, lifting elements (hook, cables..), light crane, pipes and cables where hited. Possible other modules and TA damage.	Visual channel, Radiation alarm, load alarm, Pressure drop if damage in piping. Possible loss of signal channels.
											NEAR MISS (A): Drop of load due to cable/hook failure	*Defective cable*		*Rupture of a single cable. Crane moved to safety position. Maintenance Intervention before restart of operation.*	*20*	*20*	*22*	*22*	*Lifting elements (hook, cables..), light crane*	*Visual channel, load alarm*
											Drop of load due to double blocking	Combination of failures: Defective control system (limit switches failure)+ Human failure in the application of a procedure. THERP		Load driven up to cable drums. Module drop from high position. Rupture or creep of the module. Damage to TC structure. Damage to the Connections and piping. Activated elements dispersion.	6	7	564	2220	Module, lifting elements (hook, cables..), light crane, pipes and cables where hited. If modules or TA in TC, modules and TA damage.	Visual channel, Radiation alarm, load alarm, Pressure drop if damage in piping. Possible loss of signal channels.
											NEAR MISS (A): Drop of load due to double blocking	*Limit switch system failure (crane operation too high)*		*Control room alarm. Switch system failure. Crane moved to safety position. Maintenance Intervention before restart of operation.*	*20*	*20*	*22*	*22*	*Lifting elements (hook, cables..), limit switch system, light crane.*	*Visual channel, switch system alarm.*

Fig. 62 – Part of the first RH FMECA

7. Human reliability assessment

7.1. Introduction

The perception that human factor could have a significant influence on the maintenance tasks performed by the RH system appears on the run up to RH FMECA design focused on downtime rather than safety. This importance has been highlighted in other safety analyses such as *Applying HAZOP analysis in assessing remote handling compatibility of ITER port plugs* [22], involving RH activities in the fusion framework. However, it has been never quantified. So, it was necessary to devise a new tool to estimate how the human action affects these maintenance tasks and the global downtime of the facility.

The previous labor to the method elaboration consists of an analysis of the existing documentation concerning human reliability which was found during a researching period of three weeks. Among these relevant documents some of them must be cited: *Análisis de los efectos del entrenamiento en simulador sobre la fiabilidad humana* [23]; *Best practice guide contemporary state of the scientific knowledge about human factors and labour safety in Slovakia* [24]; *Framework for human error quantification* [25]; *Human reliability analysis methods for probabilistic safety assessment* [26]; *Determination of human error probabilities for offshore platform musters* [27]; *Reactor safety study: an assessment of accident risks in US commercial nuclear power plants* [28]; *Human errors analysis and safety management systems in hazardous activities* [29] *and Probability of failure of the TRUDOCK crane system at the waste isolation pilot plant (WIPP)* [30].

All the same, the preceding reports were used to gain a first approach and to get acquainted with this field and the tools usually applied. The HRA sources really studied and used to perform and validate the method will be properly referenced below when the technique is described.

7.2. Methods to estimate the human error probability

First and foremost, a brief overview of every tool looked up and applied is submitted.

7.2.1. THERP

The Technique for Human Error Rate Prediction, THERP, is the human reliability methodology most commonly employed and the oldest one. It was described in the NUREG CR/1278 [5]. The THERP steps are like the phases used in the conventional reliability analysis where human tasks replace the mechanical components of the equipment.

In addition, these human tasks and their associated failures called Human Failure Event (HFE) have to be broken down into basic activities called Unsafe Actions (UAs) in this case. The Human Error Probability (HEP) can be estimated using assumptions for every of these UAs. Consequently, HEPs allow to obtain a failure probability for every HFE by means of a event tree (ET).

In these ETs, branches start from the bifurcation points and these bifurcation points are the UAs and whether or not the RH operators successfully perform the tasks the probability is divided as seen in the next figure.

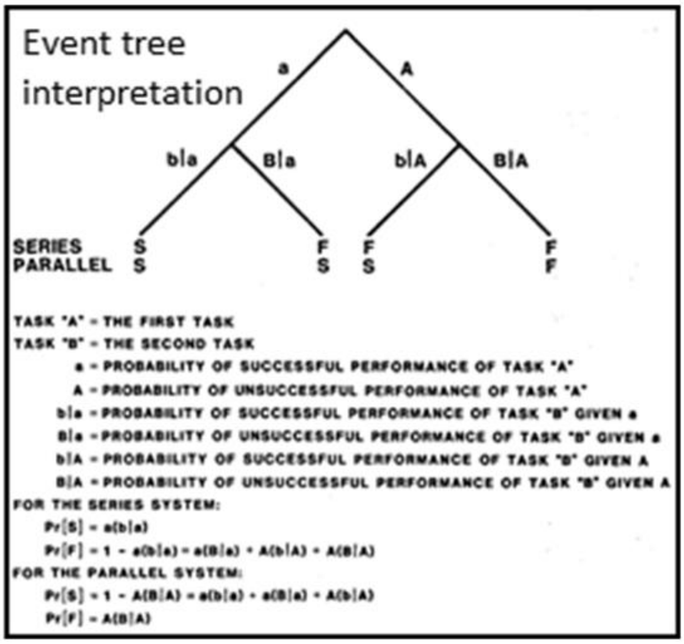

Fig. 63 – Event Tree diagram[5]

The THERP is designed to take into account the dependence between consecutive UAs and the influence by external factors called Performance Shaping Factors (PSFs). These steps will be highlighted below and the values are shown in the appendixes.

However, this technique only allows estimating the manual failure probability; for this reason, it's necessary to use another method for the cognitive part.

7.2.2. SHARP

The Systematic Human Action Reliability Procedure, SHARP [31], is the tool chosen to solve the lack of cognitive factor estimation of the previous technique. The SHARP, briefly, is the union of THERP and Human Cognitive Reliability model (HCR) which is described by the NUS-4531 document [32].

HCR is based on the premise that an operator's likelihood of success or failure in a time-critical task is dependent on the cognitive process used to make the critical decisions that determine the outcome. As happened with THERP, PSFs also influence the average (median) time taken to perform the task. Combining these factors enables "response-time" curves to be calibrated and compared to the available time to perform the task. Using these curves, the analyst can then estimate the likelihood that an operator will take the correct action, as required by a given stimulus within the available time window. The relationship between these normalized times and HEPs is based on simulator experimental data and depends on the task type: rule-based, skill-based, and knowledge-based.

In conclusion, SHARP is the starting point of the methodology used and it will be discussed further in the next section. SHARP shows that the final HEP associated to every HFE will be estimated as seen in the following figure and equation.

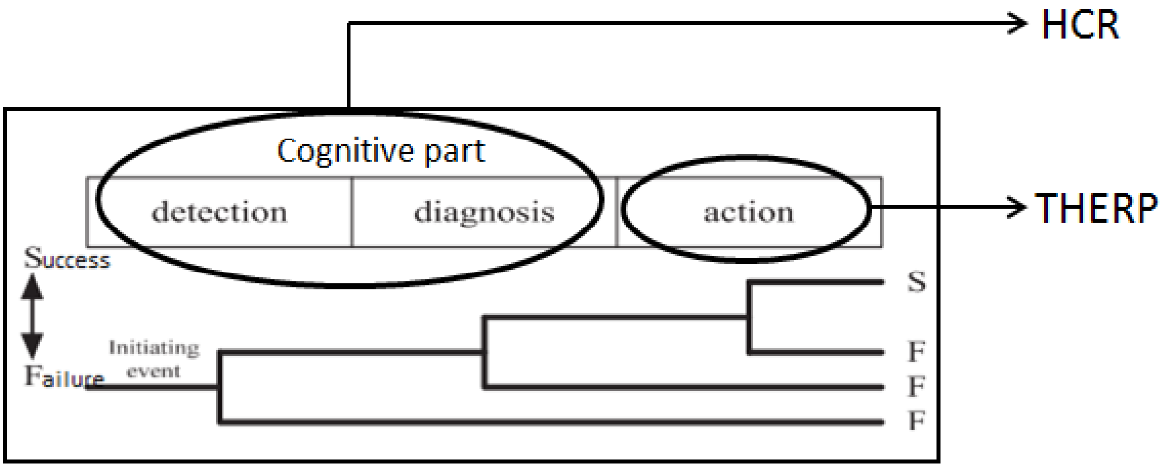

Fig. 64 – SHARP's Operator behavior model

$$HEPtotal = FP_{cog} + (1 - FP_{cog}) \cdot FP_{manual} \quad \text{(Eq. 7.1)}$$

7.2.3. ATHEANA

This method is briefly explained because it will probably be the most employed in the nuclear field as is designed to be included in Probability Safety/Risk Assessments (PSAs/PRAs).

ATHEANA is a post-incident Human Reliability Assessment (HRA) methodology developed by the US Nuclear Regulatory Commission in 2000[33]. It was developed in the hope that certain types of human behavior in nuclear plants and industries, which use similar processes, could be represented in a way in which they could be more easily understood. It seeks to provide a robust psychological framework to evaluate and identify PSFs including organizational/environmental factors which have driven incidents involving human factors, primarily with the intention of suggesting process improvement. Essentially, it is a method of representing complex accident reports within a standardized structure, which may be easier to understand and communicate.

This tool split up HFEs into basic activities called Unsafe Action (UAs) as the methodology designed and explained below. However, ATHEANA is not been used in this project since it needs the expert judgment to estimate HEPs.

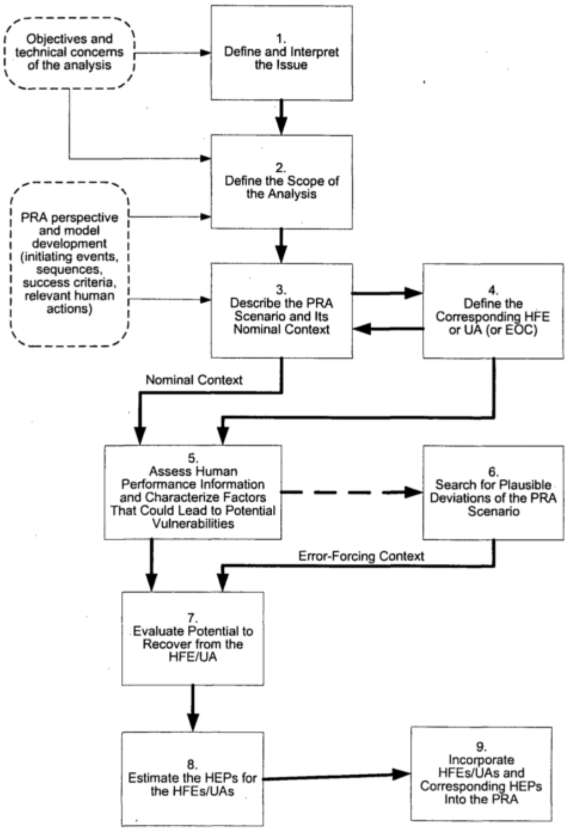

Fig. 65 – Steps in the ATHEANA methodology[33]

7.3. Selection and description of the methodology

This section describes in detail the methodology developed by the FEEL team to estimate HEPs and their associated failure rates, so as to merge HRA and RAMI analysis.

1. Identify HFEs

First and foremost, there was a selection of the Failure Modes from the first RH FMECA described above which have a partial or total cause in the human factor. So, it was crucial to create a HFE database (THERP terminology) which explains all these possible human causes. The final FMECA is shown in the *appendix A* and the HFEs are described in the *appendix E*. It is noteworthy that these HFEs must to be general and they have to allow its implementation in any component.

2. Deploy HFEs ETs

As defined in THERP and ATHEANA, every HFE is made up of different tasks called UAs. This strategy simulates the reliability analysis of technological equipment and facilities which are broken up into components. Consequently HFEs can be shown as ETs where every bifurcation is an UA with their HEP associated. Branches pointing toward left mean that the task (UA) is performed successfully while if branches pointing toward right, the human makes an error. Thus, the architecture of the HFE ET describes the procedures and the operator behavior while performing safely. This performance is supposed to follow the INPO's (Institute of Nuclear Power Operations) Human Performance Tool Box [34] [35]. This tactic is called STAR (Stop, Think, act and review) and it is mainly formed by 14 tools described below:

1) *Pre Job Briefing*: is a human performance tool that allows the worker to think through a job and use his/her knowledge to make the job as safe and efficient as possible. Workers actually involved with performing the work should prepare and lead pre-job briefs. A supervisor or foreman should be present during verbal briefings for low hazard jobs to ensure that briefing standards are met. A supervisor or manager shall be present during documented pre-job briefings for high hazard jobs to ensure that high standards are maintained during the briefing. In this project, the Pre Job Briefing has been taken into consideration in the cognitive part human error estimation.

2) *Two Minute Rule*: Recognizing abnormal conditions and identifying safety hazards is the first step to error-free and event-free performance. This tool has been taken into consideration in the cognitive part human error estimation, too.

3) *Three Way Communication*: Mutual understanding is essential to plant operation and maintenance. Therefore, responsibility for proper communication is assigned to the originator or sender, who must verify the receiver understands the message as intended. Each message that is directive in nature must use three-way communication and begins when (1st) the sender gets the attention of the intended receiver, using the person's name, and speaks the message. Then (2nd), the receiver repeats the message in a paraphrased form, which helps the sender verify that the receiver understands the intended message. Finally (3rd), the sender acknowledges that the receiver heard and understood the message. The third leg of the communication is often the weak link, since the sender is tempted to not pay attention to the receiver's statement, assuming the person heard their message. If the receiver does not receive acknowledgment from the sender, he/she should be assertive, and ask the sender to complete the third leg. Feedback is necessary to verify understanding of each spoken message. This strategy appears in some UAs with regard to communication task, between the operator and controllers, and it affects their HEP.

4) *Phonetic Alphabet*: When the only distinguishing difference between two component designators is a single letter, then the phonetic alphabet form of the letter should be substituted for the distinguishing character (A: Alpha, B: Bravo, C: Charlie…). This tool is not considered significant in this project.

5) *Procedure Use and Adherence*: Procedures help users to perform activities correctly, safely, consistently, and in accordance with design requirements. Procedures direct people's actions in a proper sequence and minimize reliance on one's memory and the choices made in the field. When workers are forced to interpret a procedure's use and applicability, the chance for error is increased. Procedure use specifies the minimum required reference to the procedure during the performance of a task, such as continuous use (in-hand), reference use, and information use. Procedure adherence means following the intent and direction provided in the procedure regardless of the level of use. These steps have been regarded in PSFs deployment.

6) *Place Keeping*: Place keeping is used to mark the steps in a procedure or work document that have been completed or that are not applicable, so that steps are not accidentally omitted or repeated. This tool has been taken into account in all the checking tasks which appears in the ETs.

7) *Flagging and Operational Barriers*: Flagging involves highlighting a component in such a way to improve the chances of performing actions on the correct component. Operational Barriers are used to mark or cover components that are not to be

worked or manipulated during an evolution. Flagging & Operational Barriers are particularly helpful when there are several similar components in close proximity to those affected by the work activity. Several events have been attributed to an individual starting an activity on one component, taking a break or becoming otherwise distracted from the component, then performing manipulations on the wrong component. This tool has been taken into consideration in HEP allocation for UAs like “Selection of the tool”.

8) *Touch STAR*: Self-checking helps prevent errors when ‘touching’ plant equipment to change its status or even when revising a document important for plant safety and reliability. Self-checking is particularly effective during skill-based tasks that could be performed without much conscious thought. This technique helps boosts attention at important points in an activity before an important action is performed. If attention is not focused, error is likely. Self-checking is constant, there are a large number of UAs of self-checking.

9) *Independent Verification*: Independent verification is the act of verifying the condition of a component, system, or document, etc., independent from the original act that placed it in that condition, to find errors by the performer. It is an act of checking a component's or product’s status or quality independent of the person that established its present state. True independence requires separation in time and space between the individuals involved to ensure ‘freedom of thought’. There are a great number of UAs of checking carried out by the controllers in this project.

10) *Concurrent Verification*: Concurrent Verification is used to prevent an error by the worker when changing the condition or status of a component. Concurrent verification focuses on the proper "verification" of the correct device, the expected operation, and the abilities of the person making the verification. Concurrent verification is intended to address every aspect of the task before any manipulation of the device is made. As already discussed in the preceding tool, there are different UAs of checking for every HFE FT.

11) *First Check*: First Check can be thought of as a remote peer check and is used to ensure the first component manipulation for a specific task is performed on the proper unit / channel / component. Simply put, First Check is used to validate you are in the right place before you begin working alone. It appears in the first UA of every HFE.

12) *Stop when Unsure*: When confronted with a situation that creates a question, a person is in uncharted (unfamiliar) territory, a knowledge-based performance situation. Whenever a question is encountered and what to do about it is uncertain,

stop and get help. Given the chances for error are particularly high in a knowledge-based situation, the best course of action, when unsure, is to take a time-out and get another person's 'mind' focused on the problem. For effective problem- solving to occur, people must recognize they are in a knowledge-based situation. This tool is related to task stopping UAs when the operator or controllers realize the error.

13) *Peer*-Checking: Peer checking is an error-prevention technique involving a verbal agreement between two individuals prior to a specific action and/or task, such that one will observe or check the behavior of the other to prevent an error by the performer. Once again, this step has been taken into consideration in checking UAs carried out by controllers and communication UAs.

14) Post-Job Review: Post-job reviews give employees that were involved in the work activity to provide feedback. A post-job review is conducted for high hazard jobs to determine if planning and briefings were effective.

As with HFEs, the UAs must to be general and they have to allow its implementation in any HFE ET. They are described in the *appendix F*. On the other hand, every FT has its own assumptions and they are shown in the *appendix G*.

3. Deploy PSFs

HEPs data that can be used in human reliability analysis and obtained from NUREG/CR-1278 [5] are nominal values. Nominal HEP is the probability of a given human error when the effects of PSFs have not been considered. In order to yield more realistic human reliability analysis, the nominal HEPs of task elements must be modified according to the task situation. This modification will be described later because this section defines PSFs selection and importance "quantification". The method follows the strategy shown in the NUREG/CR-1278 [5] and the journal *Considering performance shaping factors in situation-specific human error probabilities* [36].

In general, human behavior is affected by many factors such as adaptability, flexibility or task environment. These influences are called PSF. The base of nominal HEP modification is as follows: if the PSFs are very favorable, then the basic HEP would be determined by selecting the lower uncertainty bound of the HEP; or conversely, if the PSFs are very unfavorable, the upper uncertainty bound. The first step is to select relevant PSFs to be used in the modification of a nominal HEP. It is not possible to model all the effects of PSFs either in general or in their applications to a specific task situation. Some PSFs are more important than others in their influence on human error for a task to be analyzed. The initial consideration of PSFs should be a screening to reduce the number of possible PSFs to a practical number.

The 'quality' ($\%_i$) of a PSF represents how much adequately the condition of the PSF was designed for the performance of a task. The condition of a PSF is rated in a quality percentile score. The quality percentile score of a PSF in a specific task situation represents the percentage of all other situations (i.e., situation population) with better quality level, probably judged from experience or actual survey. Favorable PSFs are associated with low (good) percentile scores. For example, if the quality percentile score of 'information load' in a specific situation is 15%, it means that only 15% of all other situations have lower (better) score exceeding the quality level of the situation at hand.

The ‘relative importance weights’ (w_i) of PSFs are used to compute a composite quality score from the quality scores of PSFs. The relative importance weights of PSFs have values in the range [0, 1] and they sum to one. The weights have to be determined from expert opinions.

The PSFs, quality values and relative importance weights used are shown and described in the *appendix I*. The composite quality score ($\% = \sum Wi \cdot \%i$) will be used to adjust the nominal HEP as will be explained below.

4. THERP calculation: manual failure probability FP_M

To begin with, it was necessary allocate HEPs for every UA using the NUREG-1278 [5] and [25] in some case. These values are shown in the *appendix F,* in the HEPn column together with their error factor (EF). The assumptions which explain the HEPn selection and the source used are shown in the next columns.

To estimate the FP_M, the HEPn have to be modified since they are affected for the PSFs and the dependence between consecutive UAs. If the operator missed to performance some task, the failure in the next one would be more likely depending on similarity and physical/timely proximity between both actions. The dependencies between consecutive UA’s have been divided into 3 categories as explained in the THERP methodology [5]:

- Low dependency:

$$HEP_{low} = \frac{1 + 19 \cdot HEP}{20} \quad \text{(Eq. 7.2)}$$

- Medium dependency:

$$HEP_{medium} = \frac{1 + 6 \cdot HEP}{7} \qquad \text{(Eq. 7.3)}$$

- High dependency:

$$HEP_{high} = \frac{1 + HEP}{2} \qquad \text{(Eq. 7.4)}$$

The type of dependence used for every UA in every HFE is shown in the *appendix G*. However, the PSF modification has to be applied before to estimate the FP_M. This adjustment is assessed using the following equation [36]:

$$HEP_{Basic} = e^{\left[\ln\sqrt{LUB \cdot UUB} \cdot \frac{\ln\left(\frac{UUB}{LUB}\right)}{3,29} \cdot \Phi^{-1}\left[\frac{\%}{100}\right]\right]} \qquad \text{(Eq. 7.5)}$$

Being:

- $ln\sqrt{LUB * UUB}$ ≡ the log-median

- $\frac{ln\left(\frac{UUB}{LUB}\right)}{3.29}$ ≡ the log-standard distribution

- $\Phi^{-1}\left[\frac{\%}{100}\right]$ ≡ the standard manual accumulative distribution fraction

- % ≡ the composite quality score

- *LUB* and *UUB*, lower and upper bond respectively that are calculated with the associated EF found in [NUREG1278] [5].

These HEP_{basic} values are used to estimate the PF_M for every HFE, which is shown in the *appendix E.*

5. HCR calculation: cognitive failure probability FP_C

As mentioned above, this estimation has been developed using the method explained in the NUS-4531 [32] and which is applied to *HRA in China: Model and data* [37] and *Desarrollo del Análisis Probabilista de Seguridad (APS) de la piscina de combustible gastado de una central nuclear de agua a presión* [38].

HCR is a time-dependent model to be used in human cognitive processing reliability. Two hypotheses are made in it. The first is that all behavior types of human actions can be classified into skill type, rule type and knowledge type. The second is that the probability of every behavior error is only related to the proportion of permitted time to execution time ($t_d/t_{1/2}$) and is distributed by a Weibull distribution:

$$FPc = e^{-\left\{\frac{t_d/t_{1/2} - \gamma}{\alpha}\right\}^{\beta}} \quad \text{(Eq. 7.6)}$$

α, β, γ are the behavior type parameters of the RH operator and their values are procured from the Weibull distribution factors of HCR model table (NUS-4531) [32]:

Table 4 – Weibull distribution parameters depending on behavior type[37][32]

Behavior type	α	β	γ
Skill	0.407	1.2	0.7
Rule	0.601	0.9	0.6
Knowledge	0.791	0.8	0.5

At this juncture, it is important to highlight the times used and which appears in the *appendix H*:

- $\mathbf{t_{d1}}$ ≡ *time available (nominal)*: maximum time, in minutes, allowed in which the task must be performed. It was calculated dividing all the actions carried out by operators into: *move horizontally*, *move vertically*, *attachment*, *cutting/welding/bolting/unbolting*, *connection/disconnections* and *change tool*; and obtaining a “mean time available” for each one of them. The times associated with each activity are in the *appendix D*.
- $\mathbf{t_{mnom}}$ ≡ *manual action time (nominal)*: time, in minutes, estimated to carry out the task. As in the previous case, it was calculated dividing all the actions carried out by operators into: *move horizontally*, *move vertically*, *attachment*, *cutting/welding/bolting/unbolting*, *connection/disconnections* and *change tool*; and

obtaining a "mean action time" for each one of them. The current assumption is that the t_{d1} is twice t_{mnom}.

- **$t_{1/2nom}$** ≡ *detection and diagnosis time (nominal)*: this time, in minutes, is based in the STAR tools: *Pre Job Briefing* and *Two Minute Rule*. The normal value is 3 minutes; however, 10 minutes has been taken in some critical tasks.
- **t_{mbasic}** ≡ *manual action time (basic)*: time, in minutes, estimated to carry out the task altered by the new HCR PSFs (k_1, k_2, k_3). The equation and the parameters values[32] are:

$$t_{mbasic} = t_{mnom} \cdot (1 + k_1) \cdot (1 + k_2) \cdot (1 + k_3) \qquad \text{(Eq. 7.7)}$$

Table 5 – HCR PSFs values[37][32]

Operator experience (K_1)	
1. Expert, well trained	−0.22
2. Average knowledge training	0.00
3. Novice, minimum training	0.44
Stress level (K_2)	
1. Situation of grave emergency	0.44
2. Situation of potential emergency	0.28
3. Active, no emergency	0.00
4. Low activity	0.28
Quality of operator/plant interface (K_3)	
1. Excellent	−0.22
2. Good	0.00
3. Fair	0.44
4. Poor	0.78

The k_1, k_2, k_3 values used appear in the *appendix H*.

- **$t_{1/2basic}$** ≡ *detection and diagnosis time (basic)*: time, in minutes, for briefing and thinking altered by the new HCR PSFs (k_1, k_2, k_3). This value is used in the *equation 7.6*.

$$t_{1/2basic} = t_{1/2nom} \cdot (1 + k_1) \cdot (1 + k_2) \cdot (1 + k_3) \qquad \text{(Eq. 7.8)}$$

- **t_{d2}** ≡ *time available (basic)*: this time, in minutes, is determined by the *equation 7.9* and used in the *equation 7.6*:

$$t_{d2} = t_{d1} - t_{mbasic} - t_{1/2basic} \qquad \text{(Eq. 7.9)}$$

FP_Cs are in the *appendix H* (Weibull distribution column).

6. Probability calculation merging the two methodologies

The equation that links together the "action" calculations (THERP methodology) and the cognitive calculations (HCR methodology) and develops the final probability is shown in the SHARP methodology [31]:

$$HEPtotal = FPc + (1 - FPc) \cdot FP_M \quad \text{(Eq. 7.10)}$$

In all the cases, the final HEP_{total} are being strongly influenced by the "action" calculation from the THERP methodology. It is not an emergency scenario analysis where de cognitive part is highly important due to the short detection/response times.

So, the final distribution applied to the probability of HFE_{total} is a lognormal distribution with an EF value from the THERP methodology which will be used in the RAMI analysis.

7. Failure rate per event working hour calculation

To adapt these HEP_{total}s for use in RAMI analysis, it is necessary to associate a failure rate for each of them. The first step is to divide these values by the time estimated to carry out the task (t_m+$t_{1/2;}$ this last one is not relevant because its order of magnitude is much lower than the first one's value). Desired units are *failure/hour*$_{work}$.

8. Failure rate calculation

Finally, the values obtained from the previous step will be multiply by total time in which the potential failure mode with a HFE could take place. Moreover, it will be divided by the total hours in one year; thereby, the units are failure/$hour_{year}$ and they will be used in RAMI analysis like a normal component. These final values are shown in the *appendix A* in the HFE failure rate column.

7.3.1. Validation of the method in a critical task of IFMIF

The method described in the previous section had to be validated before it could be used in the IFMIF RAMI analyses. To that end, it had not only be properly referenced and procured from reliable sources but it had to be submitted to a group of experts as well.

This event happened on 28th November 2012 during 5th IFMIF Workshop hosted by ENEA and INFN in Bologna where the FEEL team successfully submits the results estimated by the methodology for the task: disconnection of the 20 helium pipes in the process of HFTM removal.

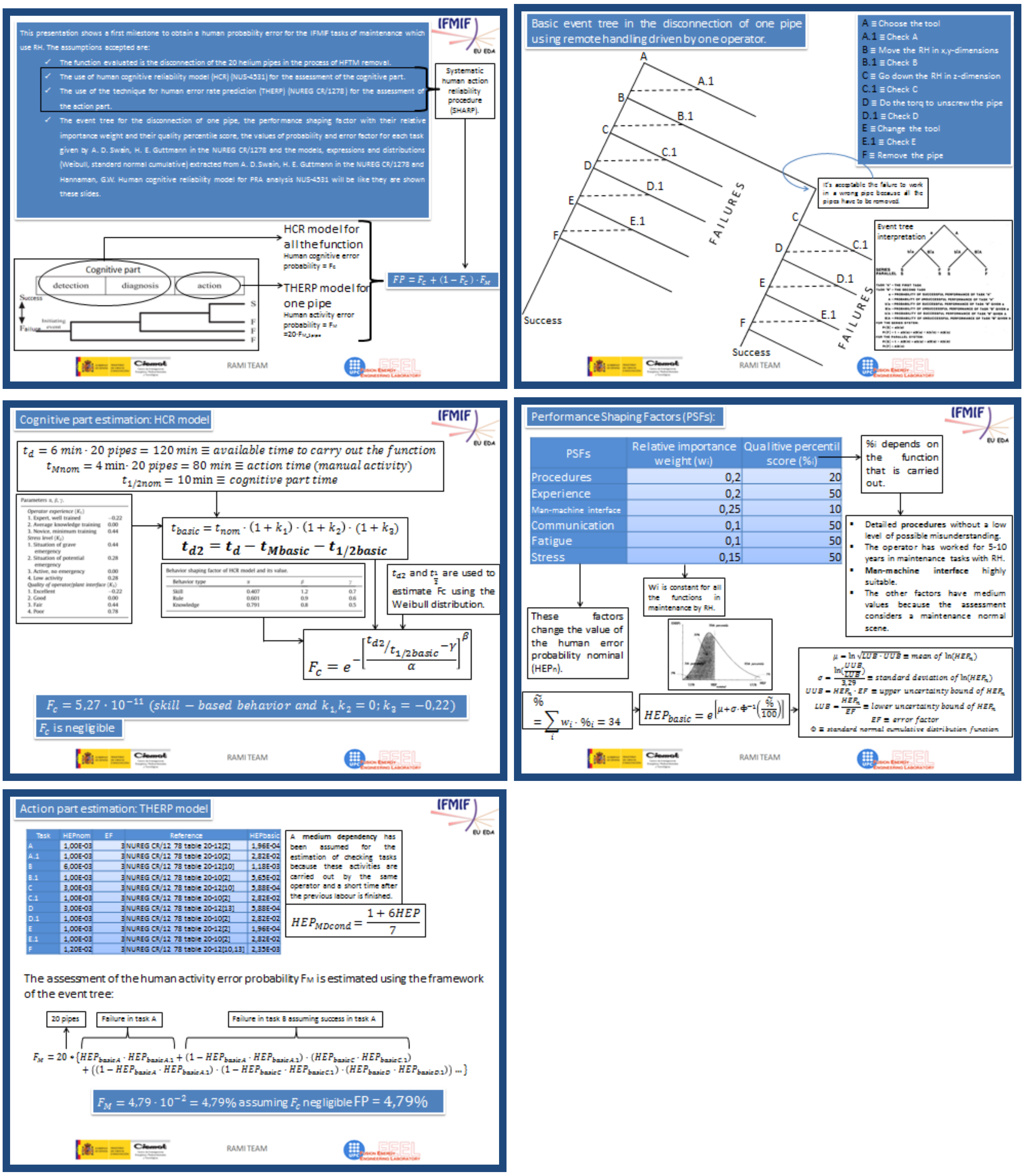

Fig. 66 – Slides used to validate the method in the 5th IFMIF Workshop

7.4. Modification of the first FMECA

Section 6.3.6 described the preliminary RH FMECA which was the starting point to ripen the project. Afterwards and at this stage, there is a need to update this first draft to be the guide of the sustainable RH FT development shown in the *appendix J*. Thus, it will be possible perform the RAMI analysis that will be easily revisable, clear and comprehensible.

The following is a brief explanation about the significant aspects which appear in the *appendix A* and improve the previous FMECA design:

- *Cause*: explains how the *potential failure modes* take place. *Causes* were foreseen in the first FMECA however they have been substantially reviewed and modified. *Causes* will be the basic events in the RAMI analysis and some of the most commonly set are: *limit switches failure*, *failure in camera element* and all HFEs. If the *potential failure mode* has two or more *causes*, they will share an AND gate since the FMECA was designed accepting this assumption.

- *Failure rate*: these FMECA's columns provide the failure frequency of components which appear as *causes* of some *potential failure modes*. Their units can be: [failure/hour$_{year}$] or [failure/demand]. These values will be the failure rates of their associated basic events inside the RAMI analysis.

- *HFE failure rate*: they are the values gotten when the methodology, previously explained, is applied. As described above, their units are [failure/hour$_{year}$].

- *References*: the *Ref* column provides the sources from components failure rates have been obtained. Once again it is noteworthy that the FEEL has succeeded creating an important failure rate and MTTR database for a large number of components used into every IFMIF facility. Consequently, some of these *failure rate* values are referenced to FEEL and their documentation.

8. HRA and RAMI merge

The FMECA approximation is useful for estimating some important issues that the system could have. However, it provides no information about other important features of the dynamics of the system under study. The FMECA analysis concludes that there will be a problem if a failure happens, but cannot give us a clear view of the effect of the whole system.

An approximate probabilistic analysis which captures these and certain other important aspects of the system which cannot be obtained from a FMECA analysis has been formulated. [7]

This analysis will be a first milestone in IFMIF RAMI assays since it is the first that contains the human factor. This stage describes the breakdown of the probabilistic simulation into the different cases, the improvements drawn from them and the final conclusions.

8.1. RiskSpectrum®

RiskSpectrum® (developed by Scandpower which is a member of the Lloyd's Register Group) is a tool specifically conceived to make PRAs/PSAs, widely used in nuclear power plant industry. So it has good capabilities to cope with similar studies for a facility like IFMIF. It allows a complete organization analysis and presentation of risk and reliability information. It is a powerful analysis tool that helps to analyze complex models in a few moments and calculate availability measures by using Boolean combination of failures modes.

8.2. Codification

Once the FMECA (*Annex A*) has been developed, the failure modes have been deployed in the implementation of a FT in RiskSpectrum® software (*Annex J*). This FT analysis consist of basic events, failures modes, unified with gates to structure the systems and to perform a simulation of the modeled design. The current model has around 428 Basic Events (*Annex K*).
An eleven characters word codification has been used to describe, the information about different aspects of the Basic Event. The codification designed by FEEL is:

Table 6 – Basic Event Codification

S	CC	F	P	L	R	XXX	M
System	Component	Function	Part	Location	Recovery time	Number	Failure Mode

This encoding is followed for the entire IFMIF facility, not only to the RH FT. A description of the characters which are assigned to this code, in RH case, is followed:

- ✓ **S (System):** The first character is about the facility/system that the Basic Event is at.

Table 7 – System codification

System	Code
Remote Handling	R

- ✓ **CC (Component):** These characters are about the RH equipment which is affected in the Basic Event.

Table 8 – Component Codification

Component	Code
Heavy Crane	HC
Light Crane	LC
Visualization System	VS

- ✓ **F (Function):** The fourth character describes the function or the element which fails.

Table 9 – Function Codification

Function/element	Code
Braking system	B
Camera	C
Defect rope/hook	D
Glass fibre cabling	G
Human	H
Illumination element	I
Motor/gearbox/shaft	M
Thermocouple	R
Switches	S
Mechanical tool	T

- ✓ **P (Part):** This character says the part of the facility that the studied component is at. In RH it is undetermined (X).

- ✓ **L (Location):** The sixth character says the component which is being manipulated.

Table 10 – Location Codification

Location	Code
TCCP	C
LSP	L
Module (1,2,3,4)	M and AM,BM,CM

PCP	P
TSP	S
TA	T

- ✓ **R (Recovery Time):** This character describes the time that takes to the system to recover in the case of a failure in the component. In RH it is undetermined (X).
- ✓ **N (Number):** These characters symbolize the order when there are some Basic Events of the same type and; in the HFEs, the number shows what of them is.
- ✓ **M (Failure Mode):** In the present RH analysis, this character is always the letter 'G' of General.

8.3. Analysis

The FT analysis searches the achievement of the availability allocation to the RH components by means of a probabilistic analysis of the RH most common activities. As mentioned above, the availability allocation objective is:

- The availability allocation for curative interventions is 99.1% during the Test Facility operation in the 11 months irradiation.
- The availability allocation for the long maintenance period is not determinate exactly but must be one so that the RH activities are achieved within the expected time (480 h). [39]

8.3.1. Assumptions

Before starting the analysis, some assumptions had to be accepted:

- The RH operation has been always simulated as continuous.
- Optimistic scenarios (downtimes) from the RH FMECA are the ones taken into account.
- There are 4 modules and all of them have the same complexity (number of feedthroughs, downtimes, operational times…). The reference design has been the HFTM.

- The HFEs improvements by means of Man Machine Interfaces (MMI) are represented as separated events in the FT. The induced error in the branch where the MMI would be located is considered assumable.

- The installation of the component “Test module positioning and supporting structure” has not been taken into account in this analysis.

8.3.2. Base Cases

The FT analysis is focused in 5 base cases. 4 out of 5 base cases describe the most common activities the RH is expected to face:

- The long maintenance case which is described in the maintenance plan consists in 20 days of downtime per 11 months of irradiation. The replacement of the irradiated modules and TA will take place among others in this period.

- The module and TA replacement curative maintenance. The TA and the irradiated modules are the critical components inside the TC. They are expected to be one of the most weak in terms of availability. Moreover, the HFTM replacement every irradiation campaign has been taken into account when allocating the systems’ availability [4] [39].

- The PCP replacement curative maintenance. Although it is expected to last all IFMIF lifetime, the PCP’s availability behavior is critical and it has been carefully analyzed.

- The long maintenance case has been analyzed again without the influence of the human factor. In other words, the only contributors to unavailability are the failure modes only related with components failure or degradation.

Figure 67 shows the behavior of the unavailability in time of the base cases. That is, the probability of having the RH system in a failed state at time t_i. First, all of their unavailabilities are not stabilized in the simulated time. In other words, the availability in the RH activities is strongly influenced by the duration of the RH operative time. Consequently, the shorter the RH activity, the better.

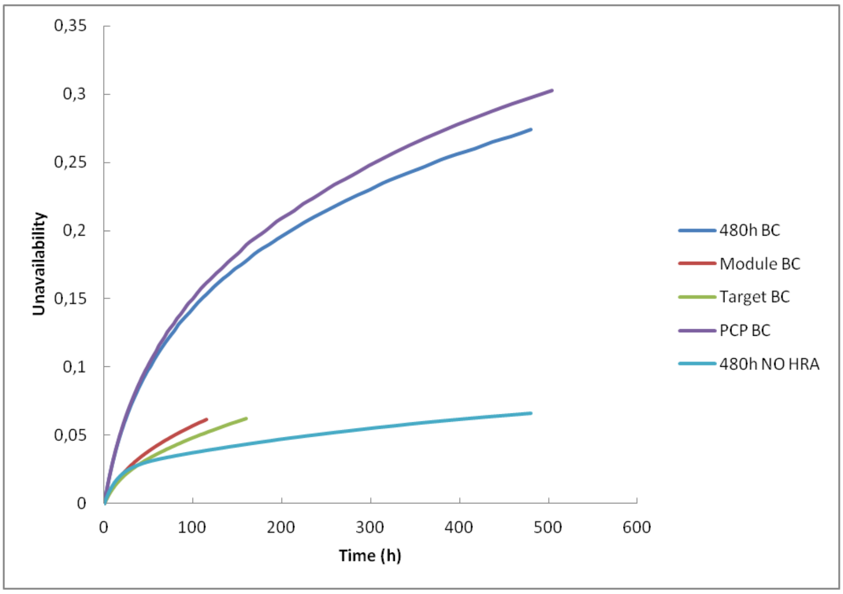

Fig. 67 – Evolution of the unavailability in the base cases

Furthermore, there are stronger slopes in the 4 base cases rather than the one belonging to the long maintenance without human factor ("480 NO_HRA"). Hence, the HFEs implementation inside the FT analysis develops in a powerful contributor to the prevention of the availability stabilization in the expected operative time. The main reason to this behavior is caused by the variation in the systems repair time and system failure rate. The HFEs have a slightly lower failure rate values (median 4E-6h^{-1}versus components median 1E-6h^{-1}) when compared to the components failure rates as shown in figure 68. Hence, the HFEs have the 75% of their values lower than 1.6E-5h^{-1} whereas the components third quadrille has a 6E-6h^{-1} value. The HFEs also generally introduce to the system scenarios where downtime is higher when compared with the ones induced by the components.

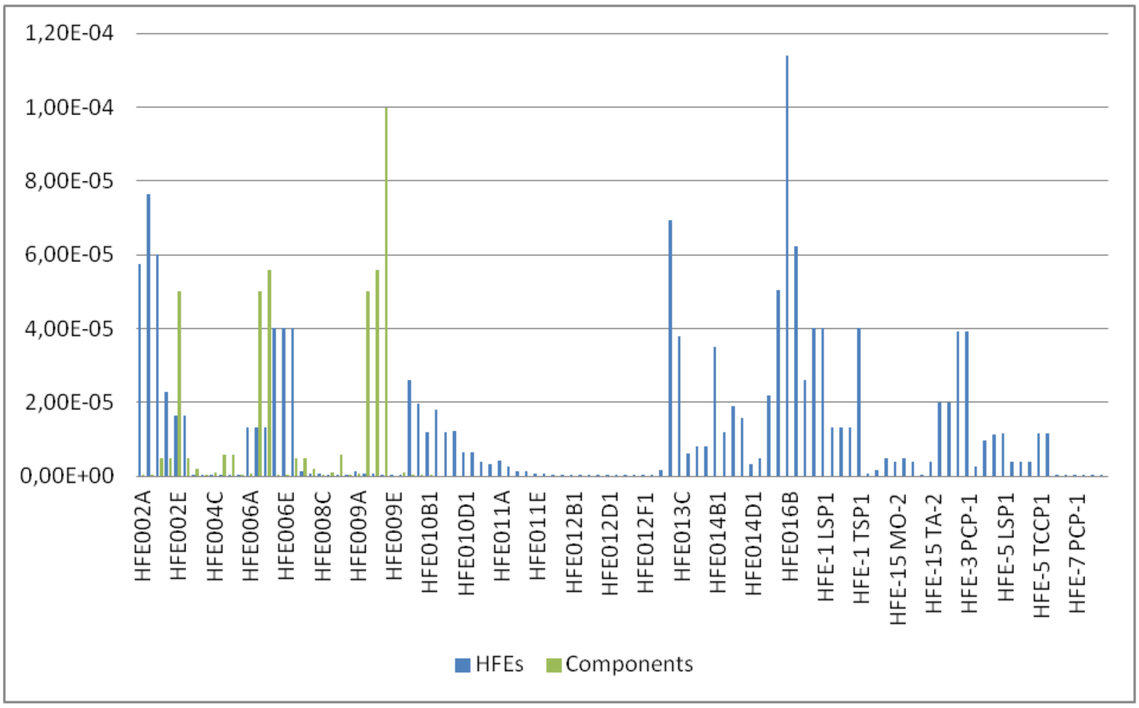

Fig. 68 – Failure rates (h^{-1}) used in the analysis

As seen in Eq. 8.1 and Eq. 8.2, the implementation of lower failure rates and higher repair times increases the addition (λ + μ). Hence the stabilization time is also increased. Furthermore, the long-term unavailability is increased, too.

$$Q(t) = \frac{\lambda}{\lambda + \mu} \cdot \left[1 - e^{1-(\lambda+\mu)\cdot t}\right] \qquad \text{(Eq. 8.1)}$$

$$Q(\infty) = \frac{\lambda}{\lambda + \mu} \qquad \text{(Eq. 8.2)}$$

Being:

Q(t), the unavailability at time t

$Q(\infty)$, the long-term unavailability

λ, the systems failure rate (h^{-1})

μ, (systems repair time)$^{-1}$

8.3.2.1. Long maintenance case, 20 days of operation

This FT analysis case describes the activities during the long maintenance shutdown programmed every eleven months of operation. The shutdown is expected to last up to 20 days (480h). The removals of the TA and the 4 modules have been simulated.

The mean availability during the 480h of operation has been 80.5%. The minimum availability at the end of the period was 72.6% with a 90% confidence interval of [44.1%, 77.8%] in the long term. The unavailability increases strongly with operation time.

This availability values are not in consonance with the expected duration range of the long shutdown as the 20 days. If we consider the mean availability (80.5%), the 480h would develop into 574h. However, the expected minimum time to develop all activities during the long maintenance plan is 347h (see FMECA, *Annex A*). As a consequence, the application of the mean availability would develop into a 414h (less than proposed 480h) but when applying the 90% confidence interval in the availability value at the end of the simulation the result is [424h,540h]. Nevertheless, an improvement in the RH design would be desirable.

The first 15 most important basic events are related with the human error in the RH operations (HFE's) and their importance is more than the 50% contribution (52.4%) to the total unavailability. The most significant families of events in order of importance are: the HFE-2 "*Drop of load due to poor or incorrect attachment of an item*" for modules and TA, the HFE-6 "*Ledging of item*" for TSP and LSP and HFE-16 "*Unintentional movement of the CMS*" for the modules. The 3 families have high failure rates >10E-5h^{-1}. Nevertheless, the first not human related event appears until the 16 position in importance (1.14%): "RHCDXLX001G" (*Drop of load due to cable/hook failure*) while moving the LSP.

Table 11 – Basic Events Importance and Sensibility Analysis of the long maintenance case

BASIC EVENTS													
nº	ID	nv	fv	fc	RDF	RDI	Sens	Sensh	sensl	Y=10X+1	BE	part	type
1	RLCHCMX200G	4,14E-02	1,10E-01	7,19E-02	1,08E+00	2,66E+00	1,76E+00	6,18E-01	3,51E-01	1,72E+00	HFE-2 modul	modul	human
2	RLCHXMX200G	4,14E-02	1,10E-01	7,19E-02	1,08E+00	2,66E+00	1,76E+00	6,18E-01	3,51E-01	1,72E+00	HFE-2 modul	modul	human
3	RLCHAMX200G	4,14E-02	1,10E-01	7,19E-02	1,08E+00	2,66E+00	1,76E+00	6,18E-01	3,51E-01	1,72E+00	HFE-2 modul	modul	human
4	RLCHBMX200G	4,14E-02	1,10E-01	7,19E-02	1,08E+00	2,66E+00	1,76E+00	6,18E-01	3,51E-01	1,72E+00	HFE-2 modul	modul	human
5	RLCHXTX200G	3,14E-02	8,36E-02	5,39E-02	1,06E+00	2,66E+00	1,56E+00	5,57E-01	3,57E-01	1,54E+00	HFE-2 modul	target	human
6	RHCHXSX600G	2,07E-02	5,50E-02	3,51E-02	1,04E+00	2,66E+00	1,36E+00	4,94E-01	3,63E-01	1,35E+00	HFE-6 TSP	TSP	human
7	RHCHXLX600G	2,07E-02	5,50E-02	3,51E-02	1,04E+00	2,66E+00	1,36E+00	4,94E-01	3,63E-01	1,35E+00	HFE-6 LSP	LSP	human
8	RHCHXLX200G	1,94E-02	5,18E-02	3,30E-02	1,03E+00	2,66E+00	1,34E+00	4,87E-01	3,64E-01	1,33E+00	HFE-2 LSP	LSP	human
9	RHCHXSX200G	8,55E-03	2,28E-02	1,44E-02	1,01E+00	2,66E+00	1,14E+00	4,24E-01	3,70E-01	1,14E+00	HFE-2 TSP	TSP	human
10	RLCHBMX160G	7,02E-03	1,87E-02	1,18E-02	1,01E+00	2,66E+00	1,12E+00	4,15E-01	3,71E-01	1,12E+00	HFE-16 modul	modul	human
11	RLCHAMX160G	7,02E-03	1,87E-02	1,18E-02	1,01E+00	2,66E+00	1,12E+00	4,15E-01	3,71E-01	1,12E+00	HFE-16 modul	modul	human
12	RLCHCMX160G	7,02E-03	1,87E-02	1,18E-02	1,01E+00	2,66E+00	1,12E+00	4,15E-01	3,71E-01	1,12E+00	HFE-16 modul	modul	human
13	RLCHXMX160G	7,02E-03	1,87E-02	1,18E-02	1,01E+00	2,66E+00	1,12E+00	4,15E-01	3,71E-01	1,12E+00	HFE-16 modul	modul	human
14	RHCHXCX600G	5,19E-03	1,38E-02	8,68E-03	1,01E+00	2,66E+00	1,09E+00	4,05E-01	3,72E-01	1,09E+00	HFE-6 TCCP	TCCP	human
15	RHCMXLX001G	5,15E-03	1,37E-02	8,61E-03	1,01E+00	2,66E+00	1,09E+00	4,04E-01	3,72E-01	1,09E+00	HFE-1 LSP	LSP	human
16	RHCDXLX001G	4,29E-03	1,14E-02	7,17E-03	1,01E+00	2,66E+00	1,07E+00	4,00E-01	3,73E-01	1,07E+00	Defective ropes or hook LSP	LSP	rope or hook

Being the most important columns:

- fv ≡ fusel-vessely importance is the ratio between the unavailability according to for all the Minimal Cut Sets not containing the basic event and the nominal top event unavailability.
- nv ≡ normal value
- fc ≡ fractional contribution to the unavailability (used in the parameter analysis)
- RDF ≡ risk decrease factor
- RDI ≡ risk increase factor
- Sensitivity

The parametric analysis of figure 69 shows low sensitivity influence in all parameters as they are all below the coherence line: y=10x+1 (proportional reference between sensitivity and importance inside RiskSpectrum®) [40].

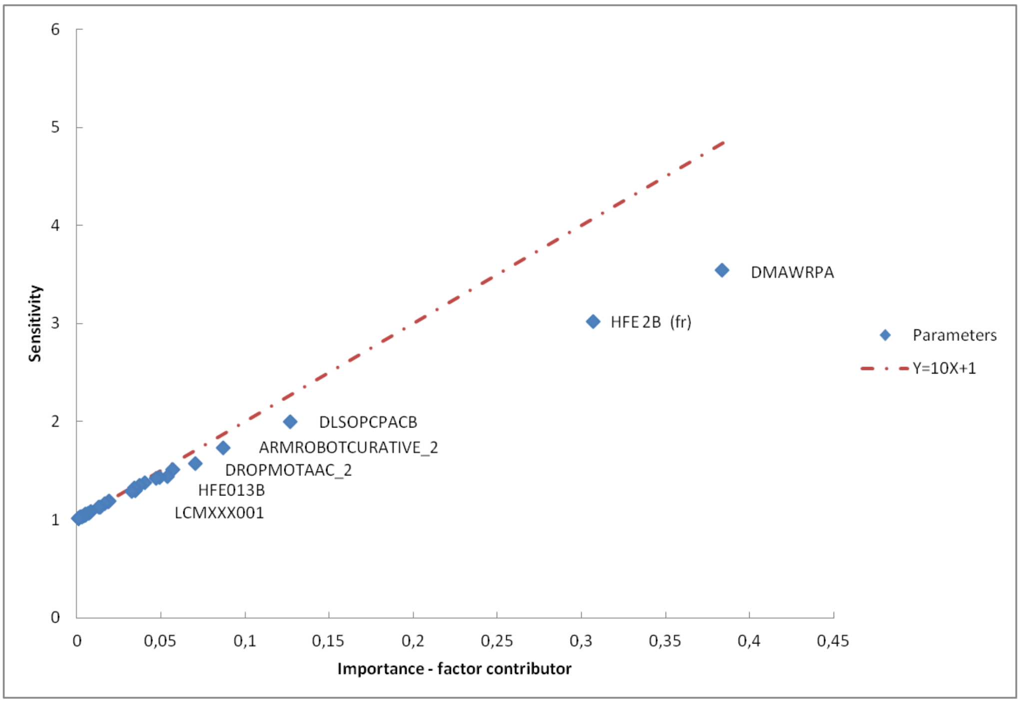

Fig. 69 – Parametric analysis of the long maintenance case

There are 4 MTTRs out of the 5 most important parameters of the simulation and their importance is more than the 50% contribution (66.9%); most of them describe drop of load scenarios in the AC. They are "DMAWRPA" (*Drop of module in AC with rupture of piping/elements inside AC*), "DLSOPCPACB" (*Drop of LSP or TSP or PCP in AC*), "ARMROBOTCURATIVE_2" (*CMS curative maintenance, safety position and major maintenance (rescue from TC)*) and "DROPMOTAAC_2" (*Drop of module or TA in AC with rupture of piping/elements inside AC*). However, these scenarios are considered optimistic as explained in the assumptions of section 8.3.1. Thus, there is no possible improvement in their value. Besides, a more conservative approach should not develop in strong variations as they are below the coherent line.

Table 12 – Parametric analysis of importance/sensibility of the long maintenance case

Parameters										
nº	ID	Parameter	nv	fc	RDF	RDI	Sens	Sensh	sensl	Y=10X+1
1	DMAWRPA	Tr	5,64E+02	3,84E-01	1,62E+00	2,66E+00	3,54E+00	8,75E-01	2,47E-01	4,84E+00
2	HFE002B	r	7,66E-05	3,07E-01	1,44E+00	2,66E+00	3,02E+00	8,24E-01	2,73E-01	4,07E+00
3	DLSOPCPACB	Tr	5,26E+02	1,27E-01	1,15E+00	2,66E+00	2,00E+00	6,64E-01	3,33E-01	2,27E+00
4	ARMROBOTCURATIVE_2	Tr	6,20E+01	8,70E-02	1,10E+00	2,66E+00	1,73E+00	6,00E-01	3,46E-01	1,87E+00
5	DROPMOTAAC_2	Tr	5,64E+02	7,07E-02	1,08E+00	2,66E+00	1,57E+00	5,53E-01	3,51E-01	1,71E+00
6	HFE013B	r	6,94E-05	5,72E-02	1,06E+00	2,66E+00	1,51E+00	5,36E-01	3,56E-01	1,57E+00
7	LCMXXX001	r	6,00E-06	5,72E-02	1,06E+00	2,66E+00	1,51E+00	5,37E-01	3,56E-01	1,57E+00
8	HFE002A	r	5,74E-05	5,39E-02	1,06E+00	2,66E+00	1,44E+00	5,13E-01	3,57E-01	1,54E+00
9	DLSOPCPACW	Tr	8,62E+02	4,96E-02	1,05E+00	2,66E+00	1,43E+00	5,12E-01	3,59E-01	1,50E+00
10	HFE016B	r	1,14E-04	4,76E-02	1,05E+00	2,66E+00	1,42E+00	5,11E-01	3,59E-01	1,48E+00
11	ARMROBOTCURATIVE_1	Tr	1,40E+01	4,09E-02	1,04E+00	2,66E+00	1,38E+00	4,97E-01	3,61E-01	1,41E+00
12	VSCXXX001	r	1,00E-04	3,77E-02	1,04E+00	2,66E+00	1,35E+00	4,89E-01	3,63E-01	1,38E+00
13	HFE006E	r	4,01E-05	3,51E-02	1,04E+00	2,66E+00	1,30E+00	4,73E-01	3,63E-01	1,35E+00
14	HFE006D	r	4,01E-05	3,51E-02	1,04E+00	2,66E+00	1,30E+00	4,73E-01	3,63E-01	1,35E+00
15	DROPMOTAAC_1	Tr	6,00E+01	3,46E-02	1,04E+00	2,66E+00	1,32E+00	4,79E-01	3,64E-01	1,35E+00
16	HFE002D	r	2,30E-05	3,30E-02	1,03E+00	2,66E+00	1,29E+00	4,68E-01	3,64E-01	1,33E+00

On the other hand, the failure rates behavior have less contribution to unavailability in the simulation with the exception of the 30.7% of the HFE-2 in module. A failure rate related to a component is not placed until the 7th position in importance. It is the “LCMXXX001” (*Defective rope or hook in the ACMC while operating with modules*).

8.3.2.2. Module replacement case, 115h of operation

This FT analysis case describes the activities during a failed module replacement. This curative maintenance intervention is believed to have a high probability of occurrence. Furthermore, the HFTM availability allocation is 98.45%. This value allows one TC opening per campaign in case the HFTM fails and needs a removal, if you consider the time to remove a module on 115h plus 10h.

The mean availability during the 115h of operation has been 96.1%. The minimum availability at the end of the period was 88.8% with a 90% confidence interval of [74.2%, 89.0%] in the long term. The unavailability increases strongly with operation time.

This availability values are not in consonance with the availability allocation (99.1%) to the RH curative interventions expected during the Test Facility operation. Hence, an improvement in the RH design is necessary.

The first 7 events are related with the human error in the RH operations (HFEs) and their importance is more than the 50% contribution (57.8%) to the total unavailability. The most important event is the HFE-2 “*Drop of load due to poor or incorrect attachment of an item*” for the module with nearly a 20% of the total contribution the unavailability. Moreover, the HFE-6 and HFE-16 appears with a high relevance as in the previous case.

The behavior of events related with the failure of components without human relation has a higher impact in this case. The "RHCMXLX001G" (*Drop of load due to motor/gearbox/shaft failure*) and the "RHCDXLX001G" (*Drop of load due to cable/hook failure*) both concerning the drops of the LSP contribute more than 5% to the unavailability.

Table 13 – Basic Events Importance and Sensibility Analysis of the module replacement case

BASIC EVENTS													
nº	ID	nv	fv	fc	RDF	RDI	Sens	Sensh	sensl	Y=10X+1	BE	part	type
1	RLCHXMX200G	4,14E-02	2,31E-01	1,98E-01	1,25E+00	5,58E+00	3,38E+00	4,98E-01	1,47E-01	2,98E+00	HFE-2 modul	modul	human
2	RHCHXSX600G	2,07E-02	1,15E-01	9,66E-02	1,11E+00	5,58E+00	2,05E+00	3,35E-01	1,64E-01	1,97E+00	HFE-6 TSP	TSP	human
3	RHCHXLX600G	2,07E-02	1,15E-01	9,66E-02	1,11E+00	5,58E+00	2,05E+00	3,35E-01	1,64E-01	1,97E+00	HFE-6 LSP	LSP	human
4	RHCHXLX200G	1,94E-02	1,08E-01	9,08E-02	1,10E+00	5,58E+00	1,98E+00	3,26E-01	1,65E-01	1,91E+00	HFE-2 LSP	LSP	human
5	RHCHXSX200G	8,55E-03	4,77E-02	3,95E-02	1,04E+00	5,58E+00	1,41E+00	2,43E-01	1,73E-01	1,40E+00	HFE-2 TSP	TSP	human
6	RLCHXMX160G	7,02E-03	3,92E-02	3,24E-02	1,03E+00	5,58E+00	1,33E+00	2,31E-01	1,74E-01	1,32E+00	HFE-16 modul	modul	human
7	RHCHXCX600G	5,19E-03	2,89E-02	2,39E-02	1,02E+00	5,58E+00	1,24E+00	2,18E-01	1,75E-01	1,24E+00	HFE-6 TCCP	TCCP	human
8	RHCMXLX001G	5,15E-03	2,87E-02	2,37E-02	1,02E+00	5,58E+00	1,24E+00	2,17E-01	1,75E-01	1,24E+00	Motor/gearbox/shaft failure LSP	LSP	Motor/gearbox/shaft
9	RHCDXLX001G	4,29E-03	2,39E-02	1,97E-02	1,02E+00	5,58E+00	1,20E+00	2,11E-01	1,76E-01	1,20E+00	Defective ropes or hook LSP	LSP	rope or hook
10	RLCHXMX132G	4,28E-03	2,39E-02	1,97E-02	1,02E+00	5,58E+00	1,20E+00	2,11E-01	1,76E-01	1,20E+00	HFE-13	modul	human
11	RLCHXMX131G	4,15E-03	2,31E-02	1,91E-02	1,02E+00	5,58E+00	1,19E+00	2,10E-01	1,76E-01	1,19E+00	HFE-13	modul	human
12	RLCHXLX102G	3,42E-03	1,91E-02	1,57E-02	1,02E+00	5,58E+00	1,16E+00	2,05E-01	1,77E-01	1,16E+00	HFE-10 LSP	LSP	human
13	RHCHXLX101G	3,42E-03	1,91E-02	1,57E-02	1,02E+00	5,58E+00	1,16E+00	2,05E-01	1,77E-01	1,16E+00	HFE-10 LSP	LSP	human
14	RLCMXMX001G	3,37E-03	1,88E-02	1,55E-02	1,02E+00	5,58E+00	1,16E+00	2,04E-01	1,77E-01	1,16E+00	Motor/gearbox/shaft failure modul	modul	Motor/gearbox/shaft
15	RLCCXMX001G	3,37E-03	1,88E-02	1,55E-02	1,02E+00	5,58E+00	1,16E+00	2,04E-01	1,77E-01	1,16E+00	Control systems failure modul	modul	Control systems
16	RHCCXLX001G	3,15E-03	1,76E-02	1,45E-02	1,01E+00	5,58E+00	1,14E+00	2,03E-01	1,77E-01	1,15E+00	Control systems failure TSP	LSP	Control systems
17	RHCCXSX001G	3,15E-03	1,76E-02	1,45E-02	1,01E+00	5,58E+00	1,14E+00	2,03E-01	1,77E-01	1,15E+00	Control systems failure LSP	TSP	Control systems
18	RHCMXSX001G	3,15E-03	1,76E-02	1,45E-02	1,01E+00	5,58E+00	1,14E+00	2,03E-01	1,77E-01	1,15E+00	Motor/gearbox/shaft failure modul	LSP	Motor/gearbox/shaft
19	RLCDXMX001G	2,81E-03	1,57E-02	1,29E-02	1,01E+00	5,58E+00	1,13E+00	2,00E-01	1,77E-01	1,13E+00	Defective ropes or hook modul	modul	rope or hook
20	RHCDXSX001G	2,62E-03	1,46E-02	1,20E-02	1,01E+00	5,58E+00	1,12E+00	1,99E-01	1,77E-01	1,12E+00	Defective ropes or hook TSP	TSP	rope or hook
21	RHCHXCX200G	2,13E-03	1,19E-02	9,77E-03	1,01E+00	5,58E+00	1,10E+00	1,95E-01	1,78E-01	1,10E+00	HFE-2 TCCP	TCCP	human
22	RHCHXSX101G	2,00E-03	1,12E-02	9,18E-03	1,01E+00	5,58E+00	1,09E+00	1,94E-01	1,78E-01	1,09E+00	HFE-10 TSP	TSP	human

The parametric analysis of figure 70 shows low sensitivity influence in all parameters as they are all below the coherence line.

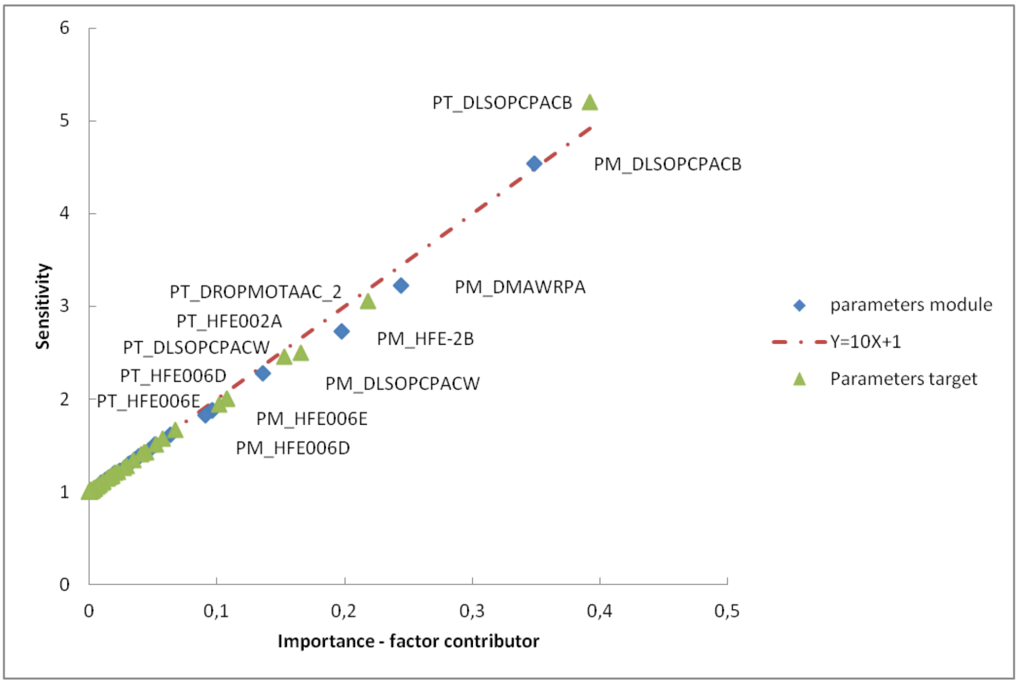

Fig. 70 – Parametric analysis of the module and target replacement case

Foremost, the figure 70 shows a similar behavior to the figure 69, where the first parameters in importance are scenarios about repair times of a drop of load. However, the human failure is more important in the module removal operations as the HFE-2 and HFE-6 contributing a total of 48.2% of the total unavailability. The modules parameters follow the same behavior as the target parameters; hence the different activities that are involved in these two types of component removal are not as important to the unavailability as the ones that are the same.

Table 14 – Parametric analysis of importance/sensibility of the module replacement case

Parameters										
nº	ID	Parameter	nv	fc	RDF	RDI	Sens	Sensh	sensl	Y=10X+1
1	DLSOPCPACB	Tr	5,26E+02	3,49E-01	1,54E+00	5,58E+00	4,54E+00	5,59E-01	1,23E-01	4,49E+00
2	DMAWRPA	Tr	5,64E+02	2,44E-01	1,32E+00	5,58E+00	3,22E+00	4,51E-01	1,40E-01	3,44E+00
3	HFE002B	r	7,66E-05	1,98E-01	1,25E+00	5,58E+00	2,73E+00	4,02E-01	1,47E-01	2,98E+00
4	DLSOPCPACW	Tr	8,62E+02	1,36E-01	1,16E+00	5,58E+00	2,28E+00	3,59E-01	1,57E-01	2,36E+00
5	HFE006E	r	4,01E-05	9,66E-02	1,11E+00	5,58E+00	1,88E+00	3,08E-01	1,64E-01	1,97E+00
6	HFE006D	r	4,01E-05	9,66E-02	1,11E+00	5,58E+00	1,88E+00	3,08E-01	1,64E-01	1,97E+00
7	HFE002D	r	2,30E-05	9,08E-02	1,10E+00	5,58E+00	1,83E+00	3,01E-01	1,65E-01	1,91E+00
8	ARMROBOTCURATIVE_2	Tr	6,20E+01	6,33E-02	1,07E+00	5,58E+00	1,61E+00	2,72E-01	1,69E-01	1,63E+00
9	ARMROBOTCURATIVE_1	Tr	1,40E+01	5,19E-02	1,05E+00	5,58E+00	1,51E+00	2,58E-01	1,71E-01	1,52E+00
10	VSCXXX001	r	1,00E-04	5,16E-02	1,05E+00	5,58E+00	1,51E+00	2,57E-01	1,71E-01	1,52E+00
11	DTCCTCWTSP	Tr	1,30E+02	4,67E-02	1,05E+00	5,58E+00	1,45E+00	2,50E-01	1,72E-01	1,47E+00
12	HFE002E	r	1,64E-05	3,95E-02	1,04E+00	5,58E+00	1,38E+00	2,38E-01	1,73E-01	1,40E+00
13	HFE013B	r	6,94E-05	3,89E-02	1,04E+00	5,58E+00	1,38E+00	2,38E-01	1,73E-01	1,39E+00
14	HCMXLX001	r	6,00E-06	3,82E-02	1,04E+00	5,58E+00	1,37E+00	2,37E-01	1,73E-01	1,38E+00
15	HCMXXX001	r	6,00E-06	3,61E-02	1,04E+00	5,58E+00	1,35E+00	2,35E-01	1,73E-01	1,36E+00
16	HFE016B	r	1,14E-04	3,24E-02	1,03E+00	5,58E+00	1,31E+00	2,28E-01	1,74E-01	1,32E+00
17	LCMXXX001	r	6,00E-06	3,11E-02	1,03E+00	5,58E+00	1,30E+00	2,27E-01	1,74E-01	1,31E+00
18	HFE006F	r	4,01E-05	2,39E-02	1,02E+00	5,58E+00	1,23E+00	2,16E-01	1,75E-01	1,24E+00

8.3.2.3. Target replacement case, 160h of operation

This FT analysis case describes the activities during a failed target replacement. The failed target replacement together with the module replacement is expected to be the curative maintenance interventions with higher probability of occurrence [39].

The mean availability during the 160h of operation has been 96.0%. The minimum availability at the end of the period was 93.8% with a 90% confidence interval of [90.0%, 75.5%] in the long term. The unavailability increases strongly with operation time as in the module replacement.

This availability values are not in consonance with the availability allocation (99.1%) to the remote handling curative interventions expected during the Test Facility operation. Hence, an improvement in the RH design is necessary.

The target replacement case behaves similar to the modules replacement. The six events with more importance are related with the human failure with a total 55.5% of unavailability contribution. Just as in the module replacement, the most important event is the HFE-2

"*Drop of load due to poor or incorrect attachment of an item*" for the target with nearly a 20% of the total contribution the unavailability.

Table 15 – Basic Events Importance and Sensibility Analysis of the target replacement case

BASIC EVENTS													
nº	ID	nv	fv	fc	RDF	RDI	Sens	Sensh	sensl	Y=10X+1	BE	part	type
1	RLCHXTX200G	3,14E-02	1,92E-01	1,66E-01	1,20E+00	6,14E+00	2,94E+00	4,07E-01	1,39E-01	2,66E+00	HFE-2 target	target	human
2	RHCHXLX600G	2,07E-02	1,27E-01	1,08E-01	1,12E+00	6,14E+00	2,19E+00	3,22E-01	1,47E-01	2,08E+00	HFE-6 LSP	LSP	human
3	RHCHXSX600G	2,07E-02	1,27E-01	1,08E-01	1,12E+00	6,14E+00	2,19E+00	3,22E-01	1,47E-01	2,08E+00	HFE-6 TSP	TSP	human
4	RHCHXLX200G	1,94E-02	1,19E-01	1,02E-01	1,11E+00	6,14E+00	2,11E+00	3,12E-01	1,48E-01	2,02E+00	HFE-2 LSP	LSP	human
5	RHCHXSX200G	8,55E-03	5,25E-02	4,43E-02	1,05E+00	6,14E+00	1,46E+00	2,28E-01	1,56E-01	1,44E+00	HFE-2 TSP	TSP	human
6	RHCHXCX600G	5,19E-03	3,18E-02	2,68E-02	1,03E+00	6,14E+00	1,27E+00	2,02E-01	1,59E-01	1,27E+00	HFE-6 TCCP	TCCP	human
7	RHCMXLX001G	5,15E-03	3,16E-02	2,66E-02	1,03E+00	6,14E+00	1,27E+00	2,02E-01	1,59E-01	1,27E+00	Motor/gearbox/shaft failure LSP	LSP	Motor/gearbox/shaft
8	RHCDXLX001G	4,29E-03	2,63E-02	2,21E-02	1,02E+00	6,14E+00	1,22E+00	1,95E-01	1,60E-01	1,22E+00	Defective ropes or hook LSP	LSP	rope or hook
9	RLCHXLX102G	3,42E-03	2,10E-02	1,76E-02	1,02E+00	6,14E+00	1,18E+00	1,89E-01	1,60E-01	1,18E+00	HFE-10 LSP	LSP	human
10	RHCHXLX101G	3,42E-03	2,10E-02	1,76E-02	1,02E+00	6,14E+00	1,18E+00	1,89E-01	1,60E-01	1,18E+00	HFE-10 LSP	LSP	human
11	RLCMXTX001G	3,37E-03	2,07E-02	1,74E-02	1,02E+00	6,14E+00	1,17E+00	1,88E-01	1,60E-01	1,17E+00	Motor/gearbox/shaft failure target	target	Motor/gearbox/shaft
12	RLCCXTX001G	3,37E-03	2,07E-02	1,74E-02	1,02E+00	6,14E+00	1,17E+00	1,88E-01	1,60E-01	1,17E+00	Control systems failure target	target	Control systems
13	RHCCXLX001G	3,15E-03	1,93E-02	1,62E-02	1,02E+00	6,14E+00	1,16E+00	1,87E-01	1,61E-01	1,16E+00	Control systems failure LSP	LSP	Control systems
14	RHCCXSX001G	3,15E-03	1,93E-02	1,62E-02	1,02E+00	6,14E+00	1,16E+00	1,87E-01	1,61E-01	1,16E+00	Control systems failure LSP	TSP	Control systems
15	RHCMXSX001G	3,15E-03	1,93E-02	1,62E-02	1,02E+00	6,14E+00	1,16E+00	1,87E-01	1,61E-01	1,16E+00	Motor/gearbox/shaft failure TSP	TSP	Motor/gearbox/shaft
16	RLCHXTX160G	3,12E-03	1,92E-02	1,61E-02	1,02E+00	6,14E+00	1,16E+00	1,87E-01	1,61E-01	1,16E+00	HFE-16 target	target	human
17	RLCDXTX001G	2,81E-03	1,73E-02	1,45E-02	1,01E+00	6,14E+00	1,15E+00	1,84E-01	1,61E-01	1,15E+00	Defective ropes or hook target	target	rope or hook
18	RHCDXSX001G	2,62E-03	1,61E-02	1,35E-02	1,01E+00	6,14E+00	1,14E+00	1,83E-01	1,61E-01	1,14E+00	Defective ropes or hook TSP	TSP	rope or hook
19	RHCHXCX200G	2,13E-03	1,31E-02	1,09E-02	1,01E+00	6,14E+00	1,11E+00	1,79E-01	1,61E-01	1,11E+00	HFE-2 TCCP	TCCP	human
20	RHCHXSX101G	2,00E-03	1,23E-02	1,03E-02	1,01E+00	6,14E+00	1,10E+00	1,78E-01	1,61E-01	1,10E+00	HFE-10 TSP	TSP	human

The events with no human failure are as in the module replacement, the "RHCMXLX001G" (*Drop of load due to motor/gearbox/shaft failure*) and the "RHCDXLX001G" (*Drop of load due to cable/hook failure*) both concerning the drop of the LSP contribute more than 5% to the unavailability.

Finally, as said in the previous case, the target parameters follow the same behavior as the module parameters. Hence, the different activities that are involved in these 2 types of component removal are not as important to the unavailability as the ones that are the same for them (e.g. the activities concerning the removal of the LSP).

Table 16 – Parametric analysis of importance/sensibility of the target replacement case

Parameters										
nº	ID	Parameter	nv	fc	RDF	RDI	Sens	Sensh	sensl	Y=10X+1
1	DLSOPCPACB	Tr	5,26E+02	3,92E-01	1,64E+00	6,14E+00	5,20E+00	5,50E-01	1,06E-01	4,92E+00
2	DROPMOTAAC_2	Tr	5,64E+02	2,18E-01	1,28E+00	6,14E+00	3,06E+00	4,01E-01	1,31E-01	3,18E+00
3	HFE002A	r	5,74E-05	1,66E-01	1,20E+00	6,14E+00	2,50E+00	3,47E-01	1,39E-01	2,66E+00
4	DLSOPCPACW	Tr	8,62E+02	1,53E-01	1,18E+00	6,14E+00	2,46E+00	3,46E-01	1,41E-01	2,53E+00
5	HFE006D	r	4,01E-05	1,08E-01	1,12E+00	6,14E+00	2,00E+00	2,94E-01	1,47E-01	2,08E+00
6	HFE006E	r	4,01E-05	1,08E-01	1,12E+00	6,14E+00	2,00E+00	2,94E-01	1,47E-01	2,08E+00
7	HFE002D	r	2,30E-05	1,02E-01	1,11E+00	6,14E+00	1,94E+00	2,88E-01	1,48E-01	2,02E+00
8	ARMROBOTCURATIVE_1	Tr	1,40E+01	6,73E-02	1,07E+00	6,14E+00	1,67E+00	2,55E-01	1,53E-01	1,67E+00
9	VSCXXX001	r	1,00E-04	5,78E-02	1,06E+00	6,14E+00	1,57E+00	2,43E-01	1,55E-01	1,58E+00
10	DTCCTCWTSP	Tr	1,30E+02	5,23E-02	1,06E+00	6,14E+00	1,51E+00	2,35E-01	1,55E-01	1,52E+00
11	HFE002E	r	1,64E-05	4,43E-02	1,05E+00	6,14E+00	1,42E+00	2,23E-01	1,56E-01	1,44E+00
12	HCMXLX001	r	6,00E-06	4,29E-02	1,04E+00	6,14E+00	1,42E+00	2,22E-01	1,57E-01	1,43E+00
13	HCMXXX001	r	6,00E-06	4,05E-02	1,04E+00	6,14E+00	1,40E+00	2,19E-01	1,57E-01	1,41E+00
14	LCMXXX001	r	6,00E-06	3,48E-02	1,04E+00	6,14E+00	1,34E+00	2,12E-01	1,58E-01	1,35E+00
15	ARMROBOTCURATIVE_2	Tr	6,20E+01	2,89E-02	1,03E+00	6,14E+00	1,28E+00	2,04E-01	1,59E-01	1,29E+00
16	HFE006F	r	4,01E-05	2,68E-02	1,03E+00	6,14E+00	1,26E+00	2,00E-01	1,59E-01	1,27E+00

8.3.2.4. PCP replacement case, 504h of operation

The PCP curative intervention and replacement is subject to controversy. It is a component not expected to be removed during the whole IFMIF operational lifetime. Although the new TC design assigns critical PCP functions as leak tightness to locations where the influence of neutron irradiation is much lower, it is prudent to study the influence of RH in its replacement. Moreover, there is a 0.014 probability of damage to the PCP in every module removal intervention when applying torque to the connection/disconnection feedthroughs. The value drops to 0.008 when the item removed is the TA. If we consider there will be at least 20 TA's removed and 100 modules (80 modules have their expected lifetime and 20 need curative replacement) removed in IFMIF's life, the probability of having a failed PCP is 1.56. Hence, there should be at least one PCP replacement as a result of RH maneuvers when connecting and disconnecting feedthroughs. This probability does not take into account other damages to the PCP (e.g. due to an impact when an item -module, TA or LSP- is dropped).

The mean availability during the 504h of operation has been 78.7%. The minimum availability at the end of the period was 69.7% with a 90% CI of [81.5%, 53.2%] in the long term. Therefore, the PCP replacement time should increase around the interval [597h, 740h] taking into account the confidence interval. The unavailability increases with the operation time but not as strongly as in the module or in the target replacements.

The first 4 events in importance are related with the drop of the modules (HFE-2) necessary to begin with the PCP removal and they contribute up to 24% of the total unavailability. Furthermore, more than the 35% of the total contribution to unavailability is done while manipulating the ACMC or the CMS. The HFE-16 and HFE-13 appear as a strong contributor to PCP unavailability, too. Thus, the inadequate connection/disconnection maneuvers lead to a higher number of actions where the risk of feedthroughs catastrophic rupture is high.

Table 17 – Basic Events Importance and Sensibility Analysis of the PCP replacement case

BASIC EVENTS													
nº	ID	nv	fv	fc	RDF	RDI	Sens	Sensh	sensl	Y=10X+1	BE	part	type
1	RLCHBMX200G	2,51E-02	8,28E-02	5,91E-02	1,06E+00	3,30E+00	1,62E+00	4,65E-01	2,87E-01	1,59E+00	HFE-2 modul	modul	human
2	RLCHAMX200G	2,51E-02	8,28E-02	5,91E-02	1,06E+00	3,30E+00	1,62E+00	4,65E-01	2,87E-01	1,59E+00	HFE-2 modul	modul	human
3	RLCHXMX200G	2,51E-02	8,28E-02	5,91E-02	1,06E+00	3,30E+00	1,62E+00	4,65E-01	2,87E-01	1,59E+00	HFE-2 modul	modul	human
4	RLCHCMX200G	2,51E-02	8,28E-02	5,91E-02	1,06E+00	3,30E+00	1,62E+00	4,65E-01	2,87E-01	1,59E+00	HFE-2 modul	modul	human
5	RHCHXPX200G	2,27E-02	7,47E-02	5,32E-02	1,06E+00	3,30E+00	1,55E+00	4,49E-01	2,89E-01	1,53E+00	HFE-2 PCP	PCP	human
6	RHCDXPX001G	1,89E-02	6,22E-02	4,41E-02	1,05E+00	3,30E+00	1,46E+00	4,24E-01	2,91E-01	1,44E+00	Defective ropes or hook	PCP	rope or hook
7	RHCHXSX600G	1,29E-02	4,25E-02	3,00E-02	1,03E+00	3,30E+00	1,31E+00	3,85E-01	2,95E-01	1,30E+00	HFE-6 TSP	TSP	human
8	RHCHXLX600G	1,29E-02	4,25E-02	3,00E-02	1,03E+00	3,30E+00	1,31E+00	3,85E-01	2,95E-01	1,30E+00	HFE-6 LSP	LSP	human
9	RHCHXLX200G	8,73E-03	2,88E-02	2,02E-02	1,02E+00	3,30E+00	1,20E+00	3,59E-01	2,98E-01	1,20E+00	HFE-2 LSP	LSP	human
10	RLCHCMX160G	7,02E-03	2,31E-02	1,62E-02	1,02E+00	3,30E+00	1,16E+00	3,48E-01	2,99E-01	1,16E+00	HFE-16 modul	modul	human
11	RLCHBMX160G	7,02E-03	2,31E-02	1,62E-02	1,02E+00	3,30E+00	1,16E+00	3,48E-01	2,99E-01	1,16E+00	HFE-16 modul	modul	human
12	RLCHAMX160G	7,02E-03	2,31E-02	1,62E-02	1,02E+00	3,30E+00	1,16E+00	3,48E-01	2,99E-01	1,16E+00	HFE-16 modul	modul	human
13	RLCHXMX160G	7,02E-03	2,31E-02	1,62E-02	1,02E+00	3,30E+00	1,16E+00	3,48E-01	2,99E-01	1,16E+00	HFE-16 modul	modul	human
14	RHCHXSX200G	5,30E-03	1,75E-02	1,22E-02	1,01E+00	3,30E+00	1,12E+00	3,37E-01	3,00E-01	1,12E+00	HFE-2 TSP	TSP	human
15	RHCHXCX600G	5,08E-03	1,67E-02	1,17E-02	1,01E+00	3,30E+00	1,12E+00	3,35E-01	3,00E-01	1,12E+00	HFE-6 TCCP	TCCP	human
16	RHCHXPX600G	4,33E-03	1,43E-02	9,99E-03	1,01E+00	3,30E+00	1,10E+00	3,31E-01	3,01E-01	1,10E+00	HFE-6 PCP	PCP	human
17	RLCHBMX132G	4,28E-03	1,41E-02	9,88E-03	1,01E+00	3,30E+00	1,10E+00	3,30E-01	3,01E-01	1,10E+00	HFE-13 module	modul	human
18	RLCHCMX132G	4,28E-03	1,41E-02	9,88E-03	1,01E+00	3,30E+00	1,10E+00	3,30E-01	3,01E-01	1,10E+00	HFE-13 module	modul	human
19	RLCHAMX132G	4,28E-03	1,41E-02	9,88E-03	1,01E+00	3,30E+00	1,10E+00	3,30E-01	3,01E-01	1,10E+00	HFE-13 module	modul	human
20	RLCHXMX132G	4,28E-03	1,41E-02	9,88E-03	1,01E+00	3,30E+00	1,10E+00	3,30E-01	3,01E-01	1,10E+00	HFE-13 module	modul	human
21	RLCHCMX131G	4,15E-03	1,37E-02	9,56E-03	1,01E+00	3,30E+00	1,10E+00	3,30E-01	3,01E-01	1,10E+00	HFE-13 module	modul	human
22	RLCHAMX131G	4,15E-03	1,37E-02	9,56E-03	1,01E+00	3,30E+00	1,10E+00	3,30E-01	3,01E-01	1,10E+00	HFE-13 module	modul	human
23	RLCHBMX131G	4,15E-03	1,37E-02	9,56E-03	1,01E+00	3,30E+00	1,10E+00	3,30E-01	3,01E-01	1,10E+00	HFE-13 module	modul	human
24	RLCHXMX131G	4,15E-03	1,37E-02	9,56E-03	1,01E+00	3,30E+00	1,10E+00	3,30E-01	3,01E-01	1,10E+00	HFE-13 module	modul	human

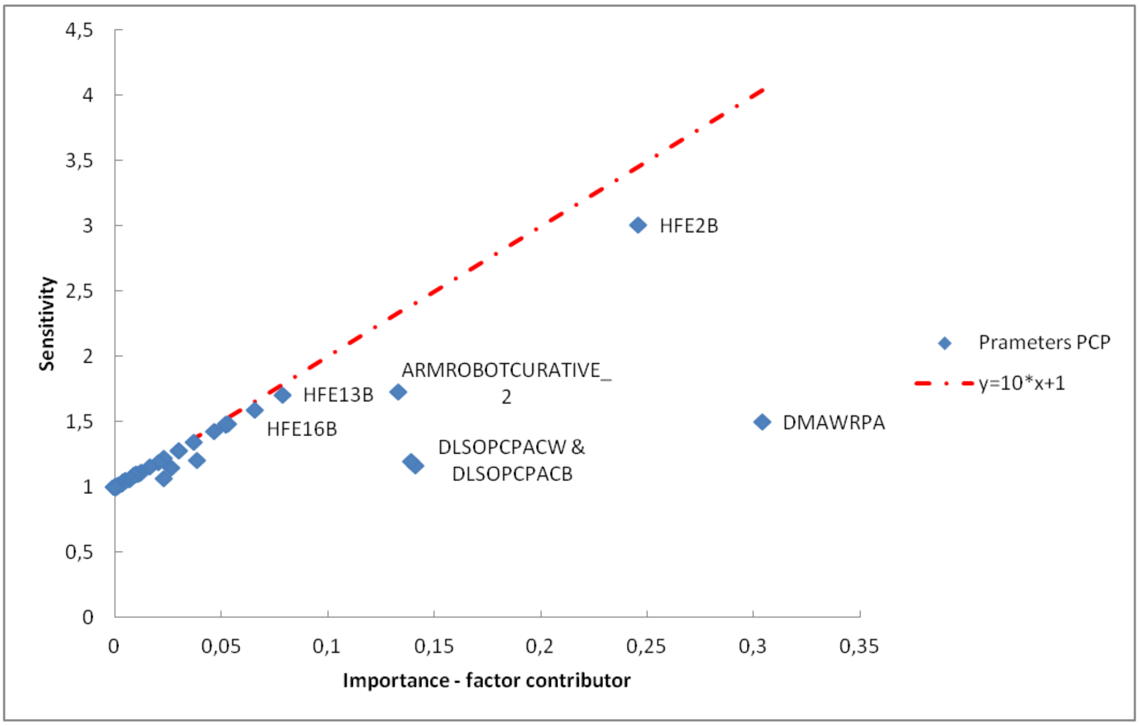

Fig. 71 – Parametric analysis of the PCP replacement intervention

Figure 71 shows that the most important parameters are related with the activities in the ACMC with the exception of the drop of big loads (PCP, LSP or TSP): “DLSOPCPACW” (*Drop of LSP or PCP in AC with rupture of piping/elements inside AC*) and “DLSOPCPACB” (*Drop of LSP or PCP in AC without rupture of piping/elements inside AC*).

8.3.2.5. Long curative maintenance case without HRA, 20 days of operation

The strong importance of the human failure has been highlighted in all base cases simulations as a common characteristic. Thus, this simulation takes place in order to describe the events describing components failures modes and their main parameters without the human factor disturbance.

The mean availability during the 480h of operation has been 95.2%. The minimum availability at the end of the period was 93.4% with a 90% confidence interval of [86.2%, 97.4%] in the long term. The unavailability increases strongly with operation time.

This availability values are not in consonance with the expected duration range of the long shutdown as the 20 days but they are in the correct direction. If we consider the mean availability (93.4%), the 480h would develop into 511h. As explained in the first case, the expected minimum time to develop all activities during the long maintenance plan is 347h. Therefore, the result is [356h, 395h] when applying the 90% confidence interval in the availability value at the end of the simulation. Nevertheless, an improvement in the RH design would be desirable as it is not feasible a perfect erase of the human factor in the RH activities.

The importance of events is not characterized by a little group of single events. Hence, all events are contributing in a similar way once the human factor has been cleared. Failure modes attaining the motor, gearbox or shaft contribute nearly the 17% of the total unavailability whereas the limit switches failures in the control systems contribute a 22%. The ropes and the hooks failures contribute a 16% since their consequences develop high downtimes. However, the top contributor group is the cameras in the visualization system (32%). The failure of a single camera develops in a very low downtime as it is not repaired in situ but replaced by a new one [1]. However, their failure has a high probability of occurrence.

Table 18 – Basic Events Importance and Sensibility Analysis of the long without HRA case

BASIC EVENTS													
nº	ID	nv	fv	fc	RDF	RDI	Sens	Sensh	sensl	Y=10X+1	BE	part	type
1	RHCMXLX001G	2,21E-03	3,35E-02	3,14E-02	1,03E+00	1,52E+01	1,32E+00	8,44E-02	6,39E-02	1,31E+00	Motor/gearbox/shaft failure LSP	LSP	Motor/gearbox/shaft
2	RLCCAMX001G	1,94E-03	2,94E-02	2,75E-02	1,03E+00	1,52E+01	1,28E+00	8,21E-02	6,42E-02	1,28E+00	Control systems failure modul	modul	Control systems
3	RLCCXTX001G	1,94E-03	2,94E-02	2,75E-02	1,03E+00	1,52E+01	1,28E+00	8,21E-02	6,42E-02	1,28E+00	Control systems failure modul	target	Control systems
4	RLCMXTX001G	1,94E-03	2,94E-02	2,75E-02	1,03E+00	1,52E+01	1,28E+00	8,21E-02	6,42E-02	1,28E+00	Motor/gearbox/shaft failure modul	target	Motor/gearbox/shaft
5	RLCMCMX001G	1,94E-03	2,94E-02	2,75E-02	1,03E+00	1,52E+01	1,28E+00	8,21E-02	6,42E-02	1,28E+00	Motor/gearbox/shaft failure modul	modul	Motor/gearbox/shaft
6	RLCMAMX001G	1,94E-03	2,94E-02	2,75E-02	1,03E+00	1,52E+01	1,28E+00	8,21E-02	6,42E-02	1,28E+00	Motor/gearbox/shaft failure modul	modul	Motor/gearbox/shaft
7	RLCMBMX001G	1,94E-03	2,94E-02	2,75E-02	1,03E+00	1,52E+01	1,28E+00	8,21E-02	6,42E-02	1,28E+00	Motor/gearbox/shaft failure modul	modul	Motor/gearbox/shaft
8	RLCCXMX001G	1,94E-03	2,94E-02	2,75E-02	1,03E+00	1,52E+01	1,28E+00	8,21E-02	6,42E-02	1,28E+00	Control systems failure modul	modul	Control systems
9	RLCCBMX001G	1,94E-03	2,94E-02	2,75E-02	1,03E+00	1,52E+01	1,28E+00	8,21E-02	6,42E-02	1,28E+00	Control systems failure modul	modul	Control systems
10	RLCMXMX001G	1,94E-03	2,94E-02	2,75E-02	1,03E+00	1,52E+01	1,28E+00	8,21E-02	6,42E-02	1,28E+00	Motor/gearbox/shaft failure modul	modul	Motor/gearbox/shaft
11	RLCCCMX001G	1,94E-03	2,94E-02	2,75E-02	1,03E+00	1,52E+01	1,28E+00	8,21E-02	6,42E-02	1,28E+00	Control systems failure modul	modul	Control systems
12	RHCMXSX001G	1,89E-03	2,87E-02	2,68E-02	1,03E+00	1,52E+01	1,27E+00	8,17E-02	6,42E-02	1,27E+00	Control systems failure modul	TSP	Control systems
13	RHCCXLX001G	1,89E-03	2,87E-02	2,68E-02	1,03E+00	1,52E+01	1,27E+00	8,17E-02	6,42E-02	1,27E+00	Control systems failure modul	LSP	Control systems
14	RHCCXSX001G	1,89E-03	2,87E-02	2,68E-02	1,03E+00	1,52E+01	1,27E+00	8,17E-02	6,42E-02	1,27E+00	Control systems failure modul	TSP	Control systems
15	RHCDXLX001G	1,84E-03	2,79E-02	2,61E-02	1,03E+00	1,52E+01	1,27E+00	8,13E-02	6,43E-02	1,26E+00	Defective ropes or hook LSP	LSP	rope or hook
16	RLCDBMX001G	1,61E-03	2,45E-02	2,30E-02	1,02E+00	1,52E+01	1,23E+00	7,94E-02	6,44E-02	1,23E+00	Defective ropes or hook LSP	modul	rope or hook
17	RLCDCMX001G	1,61E-03	2,45E-02	2,30E-02	1,02E+00	1,52E+01	1,23E+00	7,94E-02	6,44E-02	1,23E+00	Defective ropes or hook LSP	modul	rope or hook
18	RLCDXMX001G	1,61E-03	2,45E-02	2,30E-02	1,02E+00	1,52E+01	1,23E+00	7,94E-02	6,44E-02	1,23E+00	Defective ropes or hook LSP	modul	rope or hook
19	RLCDAMX001G	1,61E-03	2,45E-02	2,30E-02	1,02E+00	1,52E+01	1,23E+00	7,94E-02	6,44E-02	1,23E+00	Defective ropes or hook LSP	modul	rope or hook
20	RLCDXTX001G	1,61E-03	2,45E-02	2,30E-02	1,02E+00	1,52E+01	1,23E+00	7,94E-02	6,44E-02	1,23E+00	Defective ropes or hook LSP	target	rope or hook
21	RHCDXSX001G	1,57E-03	2,39E-02	2,24E-02	1,02E+00	1,52E+01	1,23E+00	7,90E-02	6,45E-02	1,22E+00	Defective ropes or hook LSP	TSP	rope or hook
22	RVSCCMX002G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	modul	Visualization syst.
23	RVSCCMX001G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	modul	Visualization syst.
24	RVSCXSX002G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	TSP	Visualization syst.
25	RVSCXSX001G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	TSP	Visualization syst.
26	RVSCXTX002G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	target	Visualization syst.
27	RVSCXTX001G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	target	Visualization syst.
28	RVSCXMX001G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	modul	Visualization syst.
29	RVSCXMX002G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	modul	Visualization syst.
30	RVSCBMX002G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	modul	Visualization syst.
31	RVSCXCX002G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	TCCP	Visualization syst.
32	RVSCXCX001G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	TCCP	Visualization syst.
33	RVSCAMX002G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	modul	Visualization syst.
34	RVSCBMX001G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	modul	Visualization syst.
35	RVSCXLX002G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	LSP	Visualization syst.
36	RVSCAMX001G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	modul	Visualization syst.
37	RVSCXLX001G	1,40E-03	2,12E-02	1,99E-02	1,02E+00	1,52E+01	1,20E+00	7,76E-02	6,46E-02	1,20E+00	One camera not working	LSP	Visualization syst.

Figure 72 and table 19 reveal two types of parameters in the RH components. The ones above the coherence line are parameters that have high sensitive values. Therefore, variations in their parameters will develop strong variations in the final unavailability. These are the parameters to target first in the improvement implementation.

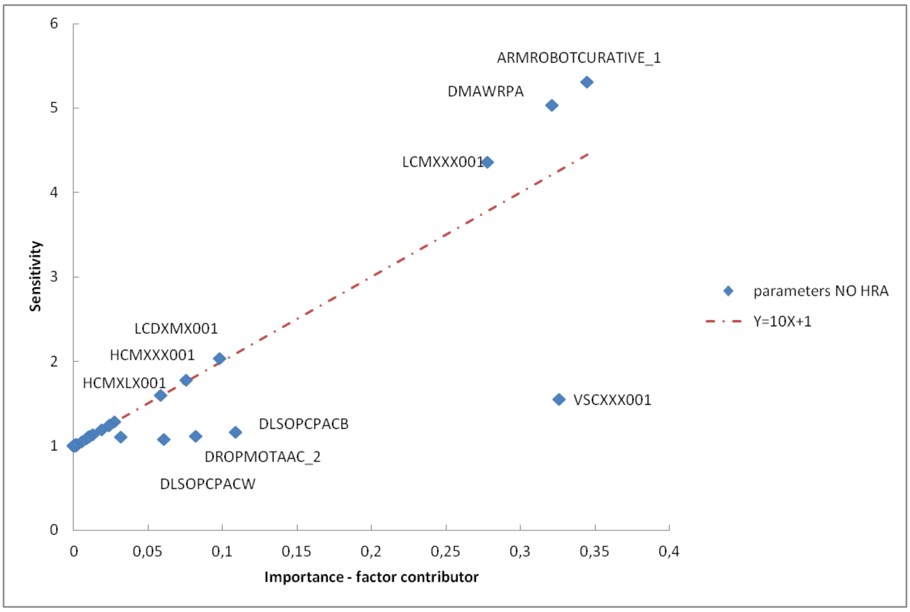

Fig. 72 – Parametric analysis of the long case without HRA

However, the first 2 targeting parameters are not available for improvement. The MTTR “ARMROBOTCURATIVE_1” (14h) refers to the downtime for fast maintenance involving the CMS (e.g. a camera removal). This parameter is strongly related with the TC length and ACMC speed, both of them are fixed. The MTTR “DMAWRPA” (564h) describes the scenario where there is a drop of an irradiated module inside the AC takes place. This parameter has huge uncertainties but is strongly related with the ability to clean the AC from irradiated small pieces. Furthermore, the calculation of the downtime has considered the optimistic case scenario of a drop inside the AC not inside the TC. Therefore, this is a fixed parameter with no way to be improved in this analysis.

Table 19 – Parametric analysis of importance/sensibility of the long case without HRA

Parameters										
nº	ID	Parameter	nv	fc	RDF	RDI	Sens	Sensh	sensl	Y=10X+1
1	ARMROBOTCURATIVE_1	Tr	1,40E+01	3,45E-01	1,53E+00	8,82E+00	5,31E+00	2,41E-01	4,54E-02	4,45E+00
2	DMAWRPA	Tr	5,64E+02	3,26E-01	1,48E+00	1,16E+00	1,55E+00	7,47E-02	4,81E-02	4,26E+00
3	VSCXXX001	r	1,00E-04	3,21E-01	1,47E+00	1,52E+01	5,03E+00	2,35E-01	4,68E-02	4,21E+00
4	LCMXXX001	r	6,00E-06	2,78E-01	1,38E+00	1,52E+01	4,36E+00	2,15E-01	4,94E-02	3,78E+00
5	DLSOPCPACB	Tr	5,26E+02	1,09E-01	1,12E+00	1,06E+00	1,16E+00	6,91E-02	5,98E-02	2,09E+00
6	LCDXMX001	r	5,00E-06	9,83E-02	1,11E+00	1,52E+01	2,03E+00	1,22E-01	6,00E-02	1,98E+00
7	DROPMOTAAC_2	Tr	5,64E+02	8,21E-02	1,09E+00	1,04E+00	1,11E+00	6,81E-02	6,13E-02	1,82E+00
8	HCMXXX001	r	6,00E-06	7,54E-02	1,08E+00	1,52E+01	1,78E+00	1,09E-01	6,13E-02	1,75E+00
9	DLSOPCPACW	Tr	8,62E+02	6,05E-02	1,06E+00	1,02E+00	1,07E+00	6,69E-02	6,28E-02	1,61E+00
10	HCMXLX001	r	6,00E-06	5,83E-02	1,06E+00	1,52E+01	1,60E+00	9,95E-02	6,24E-02	1,58E+00
11	DTCCTCWTSP	Tr	1,30E+02	3,16E-02	1,03E+00	1,09E+00	1,10E+00	7,03E-02	6,39E-02	1,32E+00
12	HCDXLX001	r	5,00E-06	2,77E-02	1,03E+00	1,52E+01	1,28E+00	8,20E-02	6,42E-02	1,28E+00
13	LCDXTX001	r	5,00E-06	2,45E-02	1,03E+00	1,52E+01	1,25E+00	8,02E-02	6,44E-02	1,25E+00
14	HCDXSX001	r	5,00E-06	2,39E-02	1,02E+00	1,52E+01	1,24E+00	7,98E-02	6,44E-02	1,24E+00
15	LCSXXX001	r	2,80E-07	1,87E-02	1,02E+00	1,52E+01	1,19E+00	7,68E-02	6,47E-02	1,19E+00
16	HCSXXX001	r	2,80E-07	1,33E-02	1,01E+00	1,52E+01	1,13E+00	7,36E-02	6,50E-02	1,13E+00
17	LCTXTX002	r	5,60E-05	1,11E-02	1,01E+00	1,52E+01	1,11E+00	7,23E-02	6,51E-02	1,11E+00
18	HCDXCX001	r	5,00E-06	1,06E-02	1,01E+00	1,52E+01	1,10E+00	7,20E-02	6,52E-02	1,11E+00
19	LCTXTX001	r	5,00E-05	9,94E-03	1,01E+00	1,52E+01	1,10E+00	7,16E-02	6,52E-02	1,10E+00
20	LCCM	Tr	2,20E+01	8,51E-03	1,01E+00	1,18E+00	1,08E+00	7,02E-02	6,53E-02	1,09E+00
21	HCCM	Tr	2,20E+01	5,39E-03	1,01E+00	1,11E+00	1,05E+00	6,86E-02	6,55E-02	1,05E+00
22	DTCCPAC	Tr	3,36E+02	2,03E-03	1,00E+00	1,00E+00	1,00E+00	6,59E-02	6,57E-02	1,02E+00
23	VSIXXX001	r	1,00E-06	1,59E-03	1,00E+00	1,52E+01	1,02E+00	6,67E-02	6,57E-02	1,02E+00
24	ARMROBOTCURATIVE_2	Tr	6,20E+01	1,23E-03	1,00E+00	1,01E+00	1,01E+00	6,62E-02	6,57E-02	1,01E+00
25	DROPMOTAAC_1	Tr	6,00E+01	1,19E-03	1,00E+00	1,01E+00	1,01E+00	6,62E-02	6,57E-02	1,01E+00
26	DMAWORPA1	Tr	6,00E+01	9,54E-04	1,00E+00	1,01E+00	1,01E+00	6,61E-02	6,57E-02	1,01E+00
27	DTSPAC	Tr	1,30E+02	5,04E-04	1,00E+00	1,00E+00	1,00E+00	6,59E-02	6,58E-02	1,01E+00
28	LCEXTX001	r	2,00E-06	3,98E-04	1,00E+00	1,52E+01	1,00E+00	6,60E-02	6,58E-02	1,00E+00
29	DTTWMT	Tr	6,00E+01	2,38E-04	1,00E+00	1,00E+00	1,00E+00	6,59E-02	6,58E-02	1,00E+00
30	LCLXTX001	r	1,00E-06	1,99E-04	1,00E+00	1,52E+01	1,00E+00	6,59E-02	6,58E-02	1,00E+00
31	LCTEXTX001	r	7,00E-07	1,39E-04	1,00E+00	1,52E+01	1,00E+00	6,59E-02	6,58E-02	1,00E+00
32	LCGXTX001	r	1,00E-07	1,99E-05	1,00E+00	1,52E+01	1,00E+00	6,58E-02	6,58E-02	1,00E+00
33	LCBXMX001	r	1,00E-08	5,49E-11	1,00E+00	1,00E+00	1,00E+00	6,58E-02	6,58E-02	1,00E+00
34	LCSXMX001_P	q	2,80E-07	5,49E-11	1,00E+00	1,00E+00	1,00E+00	6,58E-02	6,58E-02	1,00E+00
35	HCSXXX001_P	q	2,80E-07	3,48E-11	1,00E+00	1,00E+00	1,00E+00	6,58E-02	6,58E-02	1,00E+00
36	HCBXXX001	r	1,00E-08	1,93E-11	1,00E+00	1,00E+00	1,00E+00	6,58E-02	6,58E-02	1,00E+00

The next parameter to be targeted for an improvement is “LCMXXX001” which describes the failure rate of the motor/gearbox/shaft system in the ACMC. This parameter contributes nearly a 28% of the total unavailability. The other parameter to be improved should be the “LCDMX001” which describes the failure rate in the components that provide the modules attachment; the ACMCs ropes-hook system. The improvement of this parameter would induce the improvement in its related failure rate “LCDTX001” which describes the failure rate in the components that provide the target attachment. This 2 failure rates concern the ACMC sub-system and they contribute 38% of the total unavailability of the RH activities.

On the other hand, no information more reliable than the one used in this analysis (general failure 5E-6 h^{-1}) has been found about the ropes-hook system. Therefore, a serious improvement in this sub-system is difficult to expect. Furthermore, the improvement in the motor/gearbox/shaft system can imply a high cost redesign but it is achievable if needed (from 6.6E-6h^{-1} to 5E-8h^{-1} for general failure modes).

The other secondary targets would be the “HCMXXX001” and “HCMLX001”, which describe the failure rate of the motor/gearbox/shaft system in the HROC. However, these 2 parameters contribute 13% of the total unavailability and they have the same problems as described before.

The “VSCXXX001” is a special parameter. It describes the failure rate of a single camera in the visualization system of the RH. It is located in the most important contributor group. Moreover, it has a high probability of occurrence (1E-4 h^{-1}). However, it develops a low sensitive value. For this reason, a very strong effort would be needed in order to decrease this parameter importance. Yet, the camera is one of the cheapest elements in the RH system. This strong effort in increasing its reliability value could be a redundancy in all cameras (2 out of 2) and the cost would not be increased significantly. So, in this case, the redundancy strategy is specially recommended.

8.3.3. Availability Improvement

The main targeted improvements have been highlighted in the base cases analyses. There are 2 types of improvements needed. The ones that reduce human failure in the RH operations, and the ones that increase reliability in the RH equipment.

The reduction of the human failure is implemented by decreasing the influence of the following failures. The HFE-2 “Drop of load due to poor or incorrect attachment of an item” is without any doubt the primary target. The HFE-6 “Ledging of item” for TSP and LSP, the HFE-13 “Inadequate connection/disconnection” and the HFE-16 “Unintentional movement of the CMS” would be the secondary targets.

The increase in the reliability of RH equipment has its primary target in the decrease of failure rates associated to the ACMC. The parameters “LCMXXX001” and “LCDXMX001” which are describing the reliability of the motor/gearbox/shaft system and the components that provide the modules attachment are the primary target. The secondary target is to increase reliability in the same way to the HROC.

8.3.3.1. Improvement on HFE-2 "Drop of load due to poor or incorrect attachment of an item"

The HFE-2 "Drop of load due to poor or incorrect attachment of an item" improvement has been target as a primary objective. The HFE-2 describes the "*Incorrect attachment of an item"* as an item is not connected suitably. The human error can be produced as a result of a wrong position of the remote handling, a weak connection, an error when the operator choses the tool and the non-detection of these behaviors.

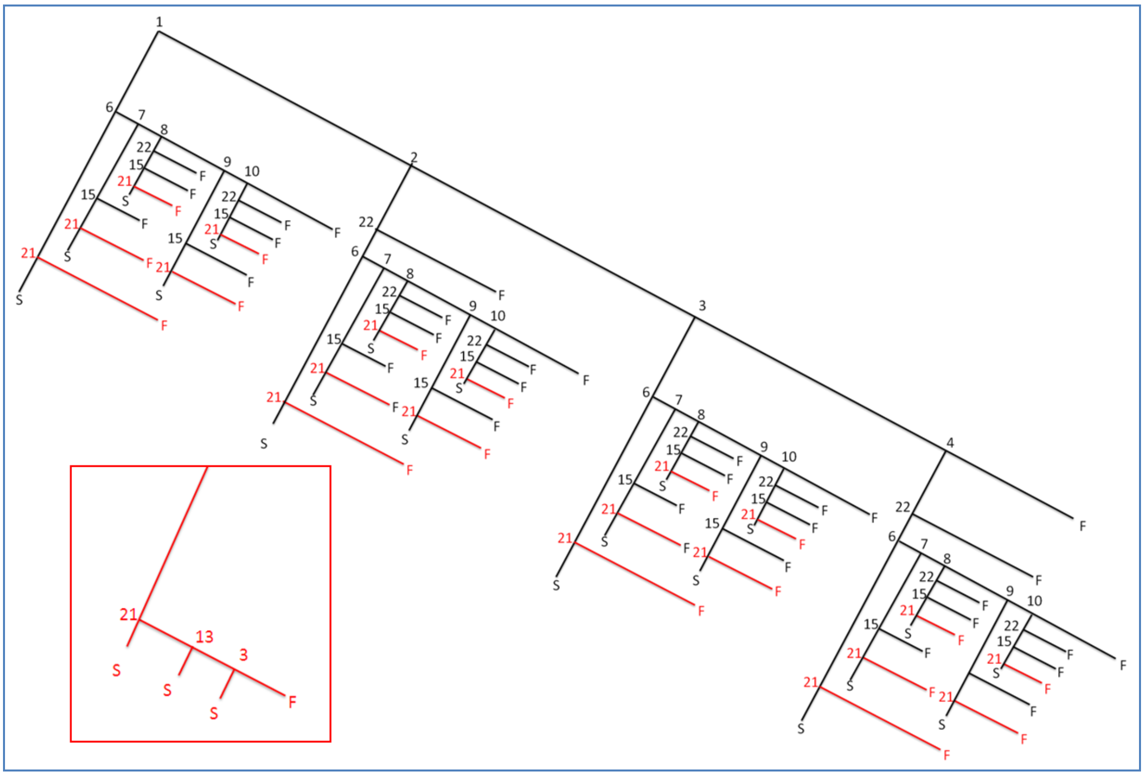

Fig. 73 – Event tree describing the behavior of the HFE-2 and improvement (UAs in the *appendix F*)

Figure 73 shows the operator is continuously checked by the controller in all actions in the procedure. The critical UA is the manual action when making physical contact between the RH tool and the item to be attached (UA number 21, *Appendix F*). The possibility of increasing reliability by increasing the controls and checks in the attachment procedure is difficult if there are no more components added to the RH activities. Furthermore, a redundant attachment system in every item would increase the reliability up to the required values. However, the lack of space in some items such as the modules TMIH makes this improvement difficult to implement.

Therefore, the improvement selected to the HFE-2 is the implementation of a device/instrumentation in the RH attachment tool or clamp. This Man Machine Interface (MMI) cited in NUREG-0554 [20] would have an interlock with alarm in the RH control room (UA 13, *Appendix F*) that would need a check from the operator to continue the operation (UA 3, *Appendix F*) as shown in the red square of figure 73. The reliability of the device/instrumentation and its interlock has been supposed as 1E-5 h^{-1} which is a standard value in electronic equipment [IAEA-TECDOC-478] [41].

Table 20 – Failure rates and confidence intervals associated with the improvement in HFE-2 by item attached

	f.r (h^{-1})	I.C. 5%	I.C. 95%
HFE002 in TA	5,74E-05	3,56E-05	1,78E-04
HFE002 in Module	7,66E-05	4,75E-05	2,37E-04
HFE002 in PCP	6,02E-05	3,73E-05	1,87E-04
HFE002 in LSP	2,30E-05	1,43E-05	7,13E-05
HFE002 in TSP	1,64E-05	1,02E-05	5,08E-05
HFE002 in TCCP	1,64E-05	1,02E-05	5,08E-05
HFE002_I in TA	2,19E-05	1,36E-05	6,79E-05
HFE002_I in Module	2,92E-05	4,75E-05	2,37E-04
HFE002_I in PCP	2,19E-05	3,73E-05	1,87E-04
HFE002_I in LSP	8,75E-06	1,43E-05	7,13E-05
HFE002_I in TSP	6,25E-06	1,02E-05	5,08E-05
HFE002_I in TCCP	6,25E-06	1,02E-05	5,08E-05

Table 20 shows the improvement in Human factor by item attached with the interlock alarm implemented. However, the HFE-2 is now linked to a component failure event which strongly increases availability; e.g. the long maintenance case increases its mean availability from 80.5% to 86.7% and what is even more important; the HFE-2 parameter drops from the 2nd unavailability contributor to the 75th place.

8.3.3.2. Improvement on HFE-6 "Ledging"

The improvement on HFE-6 "Ledging" must be implemented in the same direction as in the previous case; in other words, the HFE-6 requires an extra device/instrumentation in the RH design and an alarm with interlock in the RH control room for the RH operation.

In this case, the device could be an infrared camera/transmitter attached to the HROC and the ACMC. The path the item must move on until it is in its parking place would be monitored and if any obstacle appeared, the interlock would actuate stopping the motion and an alarm would sound in the RH control room. Similar systems have been design for ITER operation, *Conceptual Study on Flexible Guidance and Navigation for ITER Remote Handling Transport Casks* [42] and *A capacitance-based proximity sensor for whole arm obstacle avoidance* [43], not with infrared cameras but with conventional ones. The reliability of the system device/instrumentation and its interlock has been supposed as 1E-4 h^{-1}, as it is expected that the weaker component in this system would be the camera.

It seems plausible that the system is implemented for the movements for other items, although this improvement was thought for the LSP and TSP horizontal movements in the AC. The results of the improvement in the HFE-6s are shown in the next figure.

Table 21 – Failure rates and confidence intervals associated with the improvement in HFE-6 by item moved horizontally

	f.r (h^{-1})	I.C. 5%	I.C. 95%
HFE006 in TA	1,34E-05	1,07E-05	3,22E-05
HFE006 in MO	1,34E-05	1,07E-05	3,22E-05
HFE006 in PCP	1,34E-05	1,07E-05	3,22E-05
HFE006 in LSP	4,01E-05	3,21E-05	9,63E-05
HFE006 in TSP	4,01E-05	3,21E-05	9,63E-05
HFE006 in TCCP	4,01E-05	3,21E-05	9,63E-05
HFE006 in TA	1,95E-06	1,56E-06	4,68E-06
HFE006 in MO	1,95E-06	1,56E-06	4,68E-06
HFE006 in PCP	1,95E-06	1,56E-06	4,68E-06
HFE006 in LSP	5,86E-06	4,69E-06	1,41E-05
HFE006 in TSP	5,86E-06	4,69E-06	1,41E-05
HFE006 in TCCP	5,86E-06	4,69E-06	1,41E-05

Table 21 shows the improvement in Human factor by item moved with the interlock alarm implemented. Just as the HFE-2 improvement, the HFE-6 is now linked to a component failure event which strongly increases availability. For example, the long maintenance case increases its mean availability from 86.7% to 88.6%. This result seems weak. However, the availability increase highlights when compared to the only availability allocation for the RH system: 99.1% during the 11 months irradiation. The section 8.3.2.2 base case availability result (module replacement case), 96.1% increases with these improvements to 97.1%, clearly in the direction of the 99.1%. Furthermore, the HFE-6 parameter drops to the 74th place of unavailability contributors list.

8.3.3.3. Improvement on HFE-13 "Inadequate connection/disconnection"

The HFE-13 "Inadequate connection/disconnection" is not a primary target as it is not a huge contributor to the RH unavailability. Nevertheless, the possibility of a PCP failure because of a feedthrough break during the connection/disconnection process is high as seen in PCP replacement case (1.5 PCP failures during IFMIF lifetime). The HFE-13 describes the action of connecting or disconnecting inadequately and not taking it into account until the TC is in an operational state. This human failure is not involved in the events that lead to the feedthroughs break directly. However, the HFE-13 increases the number of connection/disconnection actions; hence increases the probability of occurrence of a PCP's catastrophic feedthrough failure.

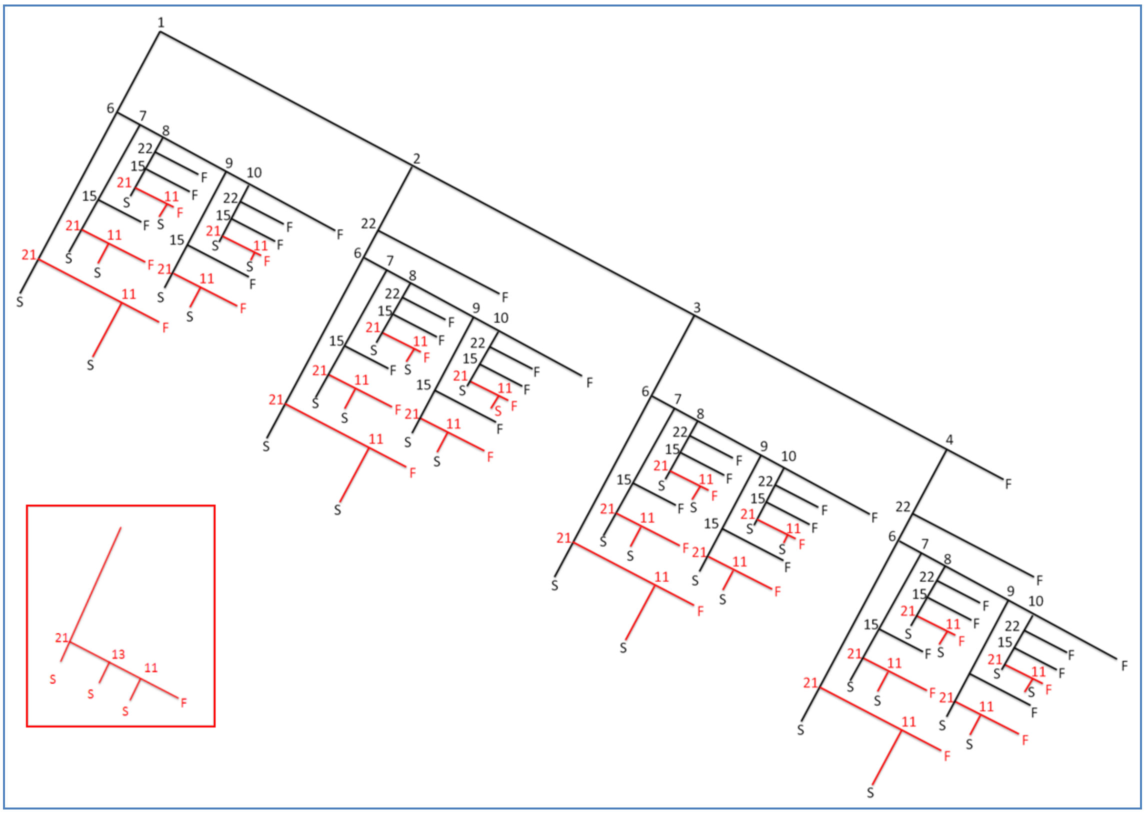

Fig. 74 – Event tree describing the behavior of the HFE-13 and improvement (UAs in the *appendix F*)

The improvement on HFE-13 must be implemented in the same direction as in the section 8.3.3.1, too. The HFE-13 event tree is similar to the HFE-2 as they both represent a chain of safe-unsafe actions that describe a human manual action (connect a tube or drop an item). Still, the HFE-13 has already a check action (UA 11, *Appendix F*) just after failing the UA 21 as shown in figure 74. The reason for this "barrier" relays on the HFE-13 repetitive occurrence. That is to say, the connection and disconnection requires a check by the controller as it is an action done many times in the same period; otherwise, the probability of failure would be strongly higher.

As a consequence, the HFE-13 requires an extra sensor/instrumentation in the RH design and an alarm with interlock in the RH control room for the RH operation. This alarm and interlock would activate when the connection or disconnection process is not entirely achieved. Just as in section 8.3.3.1, the failure rate of the sensor/instrumentation and its interlock has been supposed as 1E-5 h^{-1} which is a standard value in electronic equipment [IAEA-TECDOC-478] [41].

Table 22 – Failure rates and confidence intervals associated with the improvement in HFE-6 by item dis/connected

	f.r (h^{-1})	I.C. 5%	I.C. 95%
HFE013 in TA	1,58E-06	1,26E-06	3,79E-06
HFE013 in MO	6,94E-05	5,55E-05	1,67E-04
HFE013 in PCP	3,79E-05	3,03E-05	9,10E-05
HFE013 in LSP	6,31E-06	5,05E-06	1,51E-05
HFE013 in TA	8,74E-07	6,99E-07	2,10E-06
HFE013 in MO	3,84E-05	3,07E-05	9,22E-05
HFE013 in PCP	2,10E-05	1,68E-05	5,04E-05
HFE013 in LSP	3,49E-06	2,79E-06	8,38E-06

Table 22 shows the improvement in human factor by item connected/disconnected with the interlock alarm implemented. Just as the HFE-2 improvement, the HFE-13 is now linked to a component failure event which strongly increases availability. If all improvements made so far are compared, the long maintenance case increases its mean availability from 88.6% to 91.3%. The section 8.3.2.2 base case availability result, 96.1% increases with these improvements to 97.9%. Furthermore, the HFE-13 parameter drops to the 159th place of unavailability contributors list.

8.3.3.4. Improvement on HFE-16 "Unintentional movement of the CMS"

The improvement on the HFE-16 "Unintentional movement of the CMS" is the simplest improvement of the events related with the human factor. The state-of-art in the RH design and operation provides the recurrent solution to unintentional operator movements: the use of a virtual confinement volume. This Man Machine Interface (MMI) is a virtual confinement volume where the operator actuates and it is generated by control software integrated in the RH. If the operator moves unintentional the master device of the CMS system from the confinement volume, the slave (the proper CMS) will not move. Examples of this MMI are in JET operation and ITER design, *ITER Equatorial Port plug engineering: Design and remote handling activities supported by Virtual Reality tools* [44].

Therefore, no improvement in the HFE-16 event tree is foreseen. However, the failure rate of the software and its interlock is unknown. Hence it has been supposed a very conservative value, 1E-3 h^{-1}.

The implementation of a strategy to attack human failure has been a success. The long maintenance case increases its mean availability from 91.3% in section 8.3.3.3, to 94%. As a consequence, the human failure has only one event between the first 10 contributors which contributes only to the 6.5% of the total unavailability. Moreover, the section 8.3.2.3 base case availability result, 97.9%, increases with these improvements to 98.4%. In other words, once the human factor has been improved, the availability has risen from 96.1% to 98.4% in the way to achieve the availability allocation value: 99.1% during IFMIF irradiation.

8.3.3.5. Components Improvements

The cameras in the visualization system were highlight as the component most important contributors to unavailability in section 8.3.2.5. The reason relays in the maintenance strategy adopted in the first place. When one camera fails (and they fail often, 10E-4h^{-1}), the RH operation is stopped and the camera is changed for a new one. The downtime involved is not much (14h); however, the implication to the availability is bigger than expected.

The solution to this problem is easy and cheap. The camera is one of the cheapest elements in the RH system. Hence, a simple redundancy in all cameras (2 out of 2) is proposed as the component improvement. The simple redundancy does not require physical independent nor nuclear quality class. The proposed increase in the failure rate reliability is from 1E-4 h^{-1} to 1E-5 h^{-1}, where the most probable failure is the Common Cause Failure (CCF) of the redundant cameras.

The cameras improvement implementation develops in an increase in the mean availability in the 480h long maintenance period from 94% (previous section) to 95.8% with [82.1%,96.4%] 90% IC in the long term. The unavailability evolution is shown by improvement in the different events implementation in figure 75.

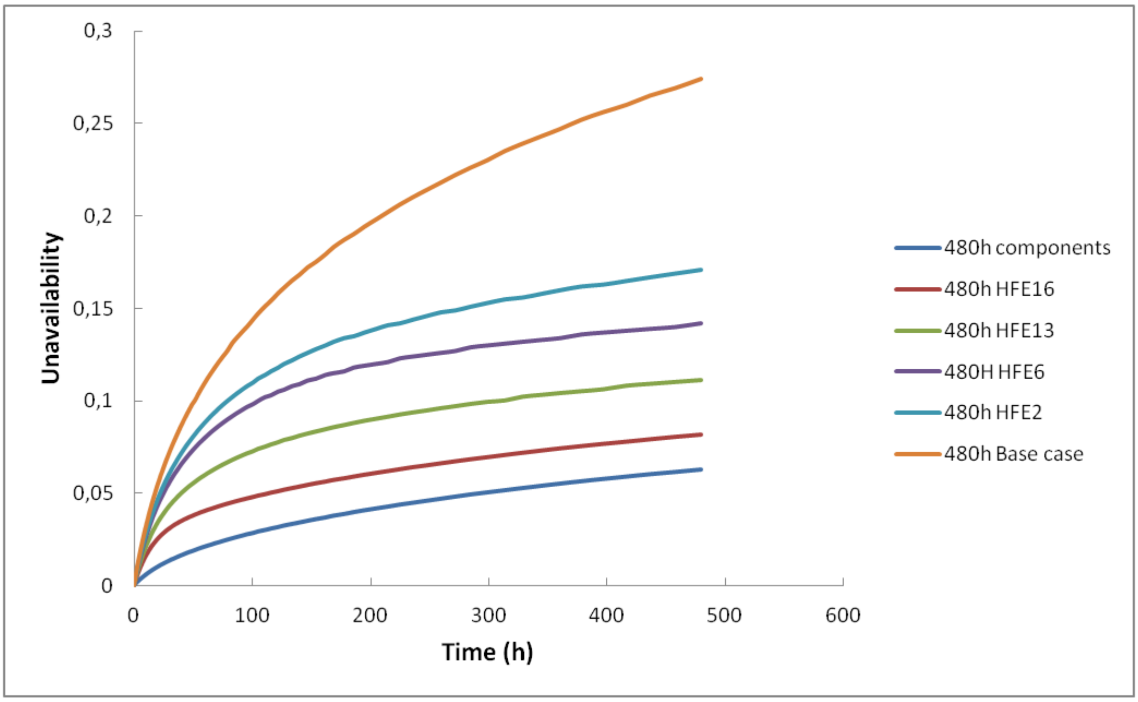

Fig. 75 – Unavailability evolution in the long maintenance case with the improvements implemented

The availability improvement is highlighted when the module removal case result is calculated for this case. The mean availability in this 115h simulation case is 99.3% with [89.7%, 98.2%] 90% IC in the long term. Thus, the mean availability result is higher than the availability allocated for the RH operation in the most probable situation, the module removal case. As a consequence, the implementation of improvements in section 8.3.3 has been a success.

The ACMC motor/gearbox/shaft system and the ropes-hook system had difficulties in their improvement implementation as seen in section 8.3.3.5. Therefore, they have not taken into account as the 99.1% availability objective from the availability allocation has been achieved.

8.3.3.6. Comparison between cranes

The RH design [DDD-III] is based on 2 “single-failure-proof” cranes operation. The selection of this type of very reliable cranes has a strong impact in the budget. In this section, a sensitivity analysis is shown comparing the availability results in the RH operation between “single-failure-proof cranes” and “normal” cranes. The design improvements described in section 8.3.3 have been considered in both cases.

Table 23 shows the failure rates used for the “single-failure-proof” and the “normal” cranes with a 90% CI. Every failure mode is more reliable in a “single failure” crane than in a "normal" one. Still the "Defective rope or hook" and the "Motor/gearbox/shaft failure" failure modes are the weakened in a stronger way.

Table 23 – Failure rates and confidence intervals in the compared cranes

		f.r (h^{-1})	I.C. 5%	I.C. 95%
Single failure crane	Limit switch / safety interlock	2,80E-07	2,37E-07	6,15E-07
	Motor/gearbox/shaft failure	6,00E-06	2,25E-06	2,25E-05
	Failure in Braking system	1,00E-08	3,75E-09	3,75E-08
	Defective rope or hook	5,00E-06	1,88E-06	1,88E-05
Normal crane	Limit switch / safety interlock	7,70E-07	6,50E-07	1,69E-06
	Motor/gearbox/shaft failure	1,00E-05	3,75E-06	3,75E-05
	Failure in Braking system	1,80E-06	6,76E-07	6,76E-06
	Defective rope or hook	3,00E-04	1,13E-04	1,13E-03

The 480h simulation reveals a decrease in availability from 95.8% with [82.1%, 96.4%] 90% IC in the long term to a 61.4% with [6.50%, 72.1%] 90% IC in the long term. Furthermore, the expected number of failures increases from 0.32 to 1.62, as seen in figure 76. In other words, there would be between 1 and 2 failures in the RH operation per maintenance period if operation is run with normal cranes. As a consequence, it is clearly unacceptable to operate with "normal" cranes in the RH operation from the RAMI point of view.

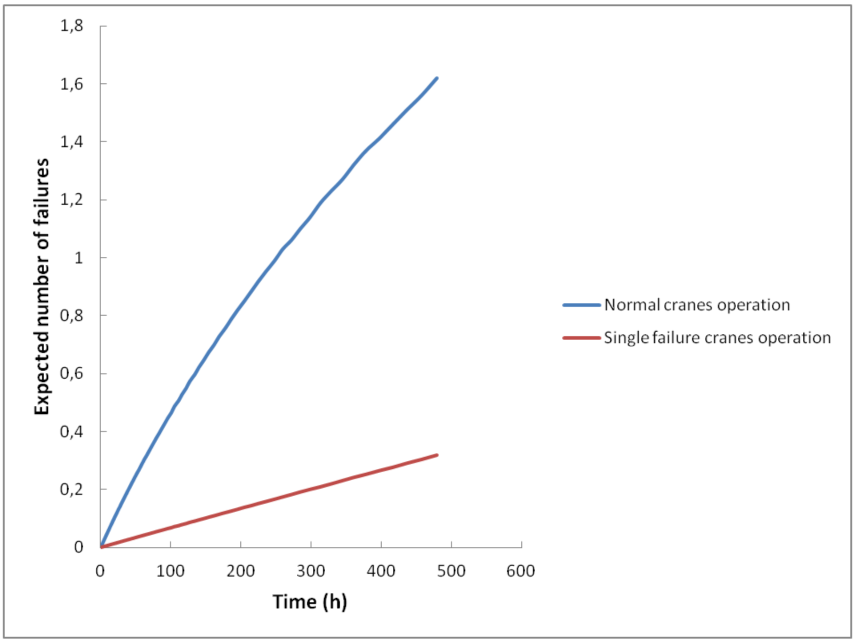

Fig. 76 – Expected number of failures in the RH operation per cranes type

Conclusion

To begin with, this section introduces the recommendations suggested from the analysis. In the HRA and RAMI merge, the RH operation has been studied in 5 base cases. In neither case, the availability objective was reached. So, a basic event and a parametric analysis for each base case were performed. As a consequence, the most important contributors to unavailability have been highlighted. Some of them could not be improved as they were already optimistic (e.g. long downtimes due to items dropped). As expected, most of the important contributors are human failure related events. However, there have been 2 types of improvements described. The ones which reduce human failure in the RH operations, and the ones that increase reliability in the RH equipment.

The design improvements are:

- The HFE-2 “Drop of load due to poor or incorrect attachment of an item” improvement consists of the implementation of a device/instrumentation in the RH attachment tool or clamp. This Man Machine Interface MMI would have an interlock with alarm in the RH control room.

- The HFE-6 “Ledging of item” improvement consists of the implementation of an infrared camera/transmitter attached to the HROC and the ACMC. The path the item must move on until it is in its parking place would be monitored and if any obstacle appeared, the interlock would actuate stopping the motion and an alarm would sound in the RH control room.

- The HFE-13 “Inadequate connection/disconnection” improvement consists of the implementation of an extra sensor/instrumentation that is able to check if the operation has finished correctly and an alarm with interlock in the RH control.

- The HFE-16 “Unintentional movement of the CMS” improvement consists of a MMI as a virtual confinement volume generated by control software integrated in the RH where the operator actuates. If the operator moves unintentional the master device of the CMS system from the confinement volume, the slave (the proper CMS) will not move.

- The RH components improvement consists on a simple redundancy in the cameras of the visualization system.

The RH design requires not only these improvements but the operation with “single-failure-proof” cranes as it is clearly unacceptable to operate with “normal” cranes from the RAMI point of view. Once these 5 improvements are taken into account, the mean availability exceeds the objective value in the availability allocation [RAMI TTC DDD-II][39] of 99.1% during TC operation. The final results are:

- The mean availability for curative interventions is 99.3% with [89.7%, 98.2%] 90% IC in the long term.
- The mean availability for the long maintenance period is 95.8% with [82.1%, 96.4%] 90% IC in the long term.

The availability is not stabilized during the simulated time (115h and 480h respectively) in neither of both cases. In other words, the availability in the RH activities is strongly influenced by the duration of the RH operative time. The shorter the RH activity, the better.

On the other hand, the drafting of the RH FMECA has shown that the human factor will have a great influence in this type of tasks, which are becoming more and more common in a lot of different fields and industries. That is why it is crucial to develop tools with which identify and quantify this human factor impact. As a result, it is acceptable to conclude that the method designed and applied in this project has been a good approach to evaluate successfully the human influence in RH maintenance tasks.

This project is a starting point, for this reason both methodology and results could be improved and used in future developments, not only in nuclear field but a lot of industries where the human factor can be important as well.

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Appendixes

A. FMECA

B. Scenarios

C. Events

D. Task Times

E. Human Failure Events database

F. Unsafe Actions database

G. Human Failure Events Event Trees and assumptions

H. Cognitive part

I. Performance Shaping Factors

J. RiskSpectrum Fault tree

K. RiskSpectrum Basic Events database

L. Cost

M. Environmental impact study